ERDC/CRREL TR-19-11

Cold Regions Research and Engineering Laboratory

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Engineer Research and Development Center

Ice Control to Prevent Flooding in Ship Creek, Alaska

Steven F. Daly, Joseph S. Rocks, Marina Reilly-Collette, and Arthur B. Gelvin

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Final Report

Prepared for 773d Civil Engineer Squadron
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Joint Base Elmendorf-Richardson
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Under MIPR F1W3EB6167G001

Abstract

Ship Creek is a steep, relatively small stream that flows through Joint Base Elmendorf-Richardson (JBER), Anchorage, Alaska. Ship Creek is a losing stream in its upper portion and a gaining stream in its lower portion, and this has significant impacts on the distribution of ice formation in the stream. Ice formation in Ship Creek is limited to the reach from roughly Vandenberg Avenue Bridge upstream to the Ship Creek Dam. This reach is steep with relatively high flow velocities. Anchor ice and ice dams form during freeze-up and raise water levels. Flooding occurs where the maximum ice-affected water level caused by anchor ice and ice dams exceeds the elevation of the top of banks of the channel. Areas outside of the channel are then inundated, with the extent determined by the elevation of the overbank areas.

There are three approaches for ice control to prevent flooding that are suitable for the flood-affected reach of Ship Creek: mechanical removal, application of well water to prevent ice formation, and natural bank restoration. This report explores these approaches and provides recommendations for their effective use.

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Preface

This study was conducted for 773d Civil Engineer Squadron, James J. Widmer, P.E., Joint Base Elmendorf-Richardson, Anchorage, Alaska, under MIPR F1W3EB6167G001.

The work was performed by the Terrain and Ice Engineering Group of the Remote Sensing / Geographic Information Systems Center of Expertise (CEERD-RS) and the Engineering Resources Branch (CEERD-RRE) of the Research and Engineering Division (CEERD-RR), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (CRREL). At the time of publication, Mr. Stephen Newman was lead, Terrain and Ice Engineering Group; Mr. David Finnegan was Chief, CEERD-RS; Dr. Caitlin Callaghan was Acting Chief, CEERD-RRE; and Mr. Jared Oren was Acting Chief, CEERD-RR. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

COL Ivan P. Beckman was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Acronyms and Abbreviations

ADF&G	Alaska Department of Fish and Game
CRREL	Cold Regions Research and Engineering Laboratory
ERDC	U.S. Army Engineer Research and Development Center
JBER	Joint Base Elmendorf-Richardson
MIAWL	Maximum Ice-Affected Water Level
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WELTS	Well Log Tracking System

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
square miles	2.589998 E+06	square meters

Executive Summary

Ice formation in Ship Creek has caused flooding at Joint Base Elmendorf-Richardson (JBER) and creates the potential for flooding each winter. The flooding has recently been prevented or mitigated by mechanical removal, using bulldozers operating in Ship Creek to remove the ice and lower the water levels. Mechanical removal has become an annual requirement.

While anecdotal reports of flooding due to ice formation describe flooding going back many decades, the first reported flooding at the fish hatchery occurred in the winter of 2004. This was soon after the Fort Richardson Power Plant had been decommissioned. Prior to the decommissioning, warm discharge from the power plant and from the Fort Richardson Fish Hatchery apparently suppressed ice production in Ship Creek and prevented any flooding at the hatchery. Significant flooding of the fish hatchery occurred in the winters of 2005–06 and 2016–17. In both cases, mechanical removal relieved the flooding. Mechanical removal effectively prevented flooding in the other years.

Ice formation in Ship Creek is limited to the reach from roughly Vandenberg Avenue Bridge upstream to the Ship Creek Dam. This reach is steep with relatively high flow velocities. The ice-formation process in this reach is typical of steep channels. The first ice formed each winter is anchor ice and ice dams. Anchor ice and ice dams both cause the water level to rise. After a number of days with frigid air temperatures, the water surface becomes completely ice covered. At this point, the *maximum ice-affected water level* in the creek is reached. Immediately afterwards, the anchor ice detaches from the channel bottom, the ice dams breach, and the water level drops. The creek then appears completely ice covered, and the water flow is confined to small passages located under the ice cover at the channel bed. The ice cover does not significantly increase or decrease from this point until spring melt out.

Flooding occurs where the maximum ice-affected water level caused by anchor ice and ice dams exceeds the elevation of the top of banks of the channel. Areas outside of the channel, adjacent to these locations, are then inundated, with the extent determined by the elevation of the overbank areas. Observations during the winter of 2016–17 showed that the water level rise caused by ice formation was contained within the Ship Creek banks from the Ship Creek Dam downstream to Grady Road Bridge and

from the upstream of the steam-line crossing downstream to below Vandenberg Avenue Bridge. The water level rise caused by ice exceeded the channel banks downstream of Grady Road Bridge to below the fish hatchery. This is the reach where flooding has been reported in previous years.

Three approaches for ice control to prevent flooding are suitable for the flood-affected reach of Ship Creek: mechanical removal, natural bank restoration, and application of well water to prevent ice formation.

Mechanical removal has successfully prevented and mitigated flooding caused by ice since the first onset of flooding in 2004. However, there are costs and disadvantages associated with operating earthmoving equipment in the Ship Creek channel. This report provides steps for optimizing the process of mechanical removal.

Increasing top-of-bank elevations to contain the maximum water levels that occur during the ice-formation period could prevent out-of-bank flooding in the flood-affected reach of Ship Creek. It was observed during winter 2016–17 that most of the ice-formation reach of Ship Creek has banks high enough to contain the channel during ice formation without flooding. There is some uncertainty in estimating the required top-of-bank elevations because the type of freeze-up process that occurs in Ship Creek is not quantitatively well described. However, the existing banks in reaches that do contain the maximum stages could be used as guides.

The Alaska Department of Fish and Game developed over twenty wells to supply water to the Fort Richardson Fish Hatchery near the flood-affected reach of Ship Creek. Calculations indicate that augmenting stream flow with well water could effectively prevent ice formation in the flood-affected reach of Ship Creek if the well production rates and groundwater temperatures that were observed during the fish hatchery operation were realized. The well water would be pumped into Flat Creek at the upstream limit of the flood-affected reach near Grady Road Bridge.

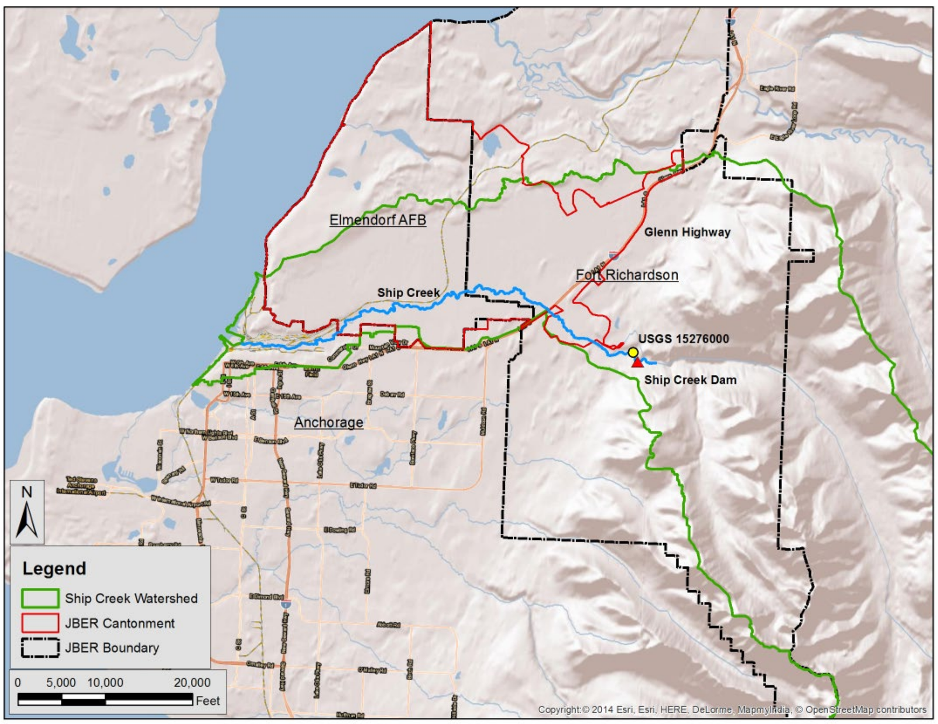
This report is the first to describe ice formation in Ship Creek and the resulting ice-affected flooding. Based on this description and the proposed approaches for ice control, it should be possible to effectively prevent ice-affected flooding along Ship Creek in JBER.

1 Introduction

1.1 Background

Joint Base Elmendorf-Richardson (JBER), Anchorage, Alaska, was formed in 2010 from the merger of the U.S. Air Force's Elmendorf Air Force Base and the U.S. Army's Fort Richardson. Ship Creek is the largest watercourse that traverses JBER (Figure 1).

Figure 1. Ship Creek location map



Ice formation in Ship Creek has caused significant flooding. Anecdotal reports of flooding from ice formation go back many decades. The earliest confirmed report described flooding at the Fort Richardson Fish Hatchery in winter 2004. This was soon after the Fort Richardson Power Plant had been decommissioned. Prior to the decommissioning, warm discharge from the power plant and from the Fort Richardson Fish Hatchery apparently suppressed ice production in Ship Creek and prevented flooding downstream. This suggests that the anecdotal reports were of flooding upstream of Grady Road Bridge. However, significant flooding occurred near the fish hatchery during the winters of 2005–06 and 2016–17. In both cases, mechanical removal using bulldozers operating in the creek relieved the flooding. Mechanical removal effectively prevented flooding in the other years since the practice was initiated in 2004 and has become an annual JBER requirement to prevent flooding.

Ship Creek is unique in that ice formation is limited to the upstream portion of the creek as it flows through JBER. This upstream portion is referred to as the *ice-formation reach*. The downstream portion of Ship Creek remains largely ice-free throughout the winter, apparently caused by the influx of groundwater. Ice formation in Ship Creek is characteristic of ice formation in steep channels; it is dominated by anchor-ice formation, ice-dam formation, and a continuous increase in water level with time throughout the ice-formation reach until the *maximum ice-affected water level* (MIAWL) is reached. Throughout most of the ice-formation reach, the MIAWL is contained within the channel banks. Flooding occurs in the section of Ship Creek where the maximum water levels are not contained by the channel banks, from approximately Grady Road Bridge to downstream of the Alaska Department of Fish and Game (ADF&G) Fish Hatchery (now closed)

Three approaches for ice control to prevent flooding are suitable for the flood-affected reach of Ship Creek: mechanical removal, bank modification, and thermal suppression by applying well water to prevent ice formation. While mechanical removal can successfully prevent and mitigate flooding caused by ice, there are number of costs and disadvantages associated with operating earthmoving equipment in the Ship Creek channel.

Alternatively, out-of-bank flooding could be prevented in the flood-affected reach of Ship Creek if the top-of-bank elevations were increased to contain the maximum water levels that occur during the ice-formation period. It was observed during the winter of 2016–17 that most of the ice-formation reach of Ship Creek has banks high enough to contain the flow in the channel during ice formation without flooding. There is some uncertainty in estimating the required top-of-bank elevations because the type of freeze-up process that occurs in Ship Creek is not quantitatively well described. However, the existing banks in reaches that do contain the maximum stages could be used as guides.

Additionally, there are over twenty wells that ADF&G developed to supply water to the Fort Richardson Fish Hatchery near the flood-affected reach of Ship Creek. Calculations indicate that well water could be effective in preventing ice formation in the flood-affected reach of Ship Creek if the well production rates and groundwater temperatures observed during the fish hatchery operation were realized. The well water would be pumped into Flat Creek at the upstream limit of the flood-affected reach near Grady Road Bridge.

1.2 Objective

The primary objectives of this report are to understand the ice-formation process in Ship Creek, to determine how ice formation leads to flooding, and to describe measures that are likely to successfully prevent ice-affected flooding along Ship Creek in JBER, Anchorage, Alaska.

1.3 Approach

This report investigates alternatives to mechanical removal for preventing flooding caused by ice formation in Ship Creek. In doing so, it covers the following topics:

1. A brief review of the chronology of development along Ship Creek (important, given the rapid and extensive building and the subsequent modifications that occurred on Elmendorf Air Force Base and Fort Richardson starting in World War II)
2. A description of flooding due to ice formation
3. The relevant attributes of the Ship Creek Watershed, including its winter weather, hydrology, and groundwater resources
4. The ice-formation process in Ship Creek
5. Three approaches for ice control
6. Steps for optimizing the process of mechanical removal

2 Chronology of Ship Creek Development

The history of hydraulic structures, power-plant operations, and well development in the Ship Creek watershed is important background information for the current ice problems. Table 1 outlines the development of Ship Creek. The locations of structures listed in the table are shown in Figure 2. Development started near the downstream end of the creek at Knik Arm with the establishment of the Alaska Engineering Commission Headquarters around 1915. Significant development in the reaches of Ship Creek currently located on Joint Base Elmendorf-Richardson did not begin until World War II. This development continued throughout the Cold War from the 1950s through 1980s (Waddell 2003).

The most significant developments impacting the stream hydrology were the construction of several dams and stream-side power plants in the 1940s and 1950s. The Elmendorf Power Plant was constructed in 1945 followed by the Fort Richardson Power Plant in 1952 (Figure 3). A run-of-river small dam was constructed with each power plant to divert water from Ship Creek for cooling. A small bridge carrying a steam line across Ship Creek was also built at this time. The current Ship Creek Dam was constructed in 1954 to provide potable water for the base and the City of Anchorage. The Knik Arm Power Plant Dam was constructed in 1952 on Ship Creek immediately upstream of its outlet in Knik Arm.

Fish hatcheries were built alongside the Elmendorf and the Fort Richardson Power Plants to take advantage of the warm effluent from the plants (Inter-Fluve, Inc., 2007). The Fort Richardson State Fish Hatchery was built in 1958 (ADF&G 2017b) and the Elmendorf State Hatchery in 1965 (ADF&G 2017a). In 1984, ADF&G expanded the Fort Richardson State Fish Hatchery. All the water used in the Fort Richardson State Fish Hatchery came from two well fields and two deep wells—22 wells in all. The warm effluent from the power plants was used to heat a portion of the well-water flow.

The Knik Arm Power Plant was decommissioned in the 1980s, and the ADF&G now operates the Knik Power Plant Dam. The Fort Richardson Power Plant was decommissioned in 2003 and the Elmendorf Power Plant in 2006. The supply of the power plants' warm effluent to the fish hatcheries ceased when the plants were decommissioned. The Fort Richardson State Fish Hatchery was able to operate for 11 more years entirely on well water without the benefit of the heated effluent. It closed in 2014. The William Jack Hernandez Sport Fish Hatchery was completed in 2011 and replaced the Elmendorf State Hatchery, which closed at that time (ADF&G 2017c). The Fort Richardson Power Plant run-of-river small dam was removed in January 2015. The steam-line crossing remains in place but is no longer in use.

Table 1. Chronology of Ship Creek development.

Date	Event
29 Apr. 1939	Fort Richardson established by Executive Order 8102.
1943	Original wooden-crib Ship Creek Dam constructed.
~1945	Elmendorf Power Plant constructed (Exact year uncertain). Small dam constructed to impound cooling water for plant.
1952	Fort Richardson Power Plant constructed. Small dam constructed to impound cooling water for plant.
1952	Knik Arm Power Plant Dam constructed.
1954	Concrete Ship Creek Dam completed, replacing wooden-crib dam.
1956–57	Fort Richardson supply wells installed.
1957	Secretary of the Army approved a cooperative agreement between the Army, the Alaska Territorial Department of Fish and Game, and the Fort Richardson Power Plant, allowing the plant’s cooling pond to be used for rearing fish.
1958	U.S. Army built Fort Richardson State Fish Hatchery to provide fish for post lakes.
Early 1960s	ADF&G became involved with Fort Richardson State Fish Hatchery and assumed full operation by the late 1960s.
1965	ADF&G Elmendorf State Hatchery first opened.
1969	Fort Richardson Power Plant converted to natural gas.
1971–76	ADF&G “Old” well field installed at Fort Richardson State Fish Hatchery.
1976	Elmendorf State Hatchery expanded by ADF&G.
1980–82	ADF&G “New” well field installed at Fort Richardson State Fish Hatchery.
1984	ADF&G expanded Fort Richardson State Fish Hatchery.
~1985	Knik Arm Power Plant decommissioned (exact year uncertain).
31 Oct. 2003	Fort Richardson Power Plant decommissioned.
2006	Elmendorf Power Plant decommissioned.
2011	Elmendorf State Hatchery closed.
Jun. 2011	William Jack Hernandez Sport Fish Hatchery completed.
Nov. 2014	Fort Richardson State Fish Hatchery closed. ADF&G well fields shut down.
Jan. 2015	Removal of Fort Richardson Power Plant small dam.

Figure 2. Ship Creek locations map.

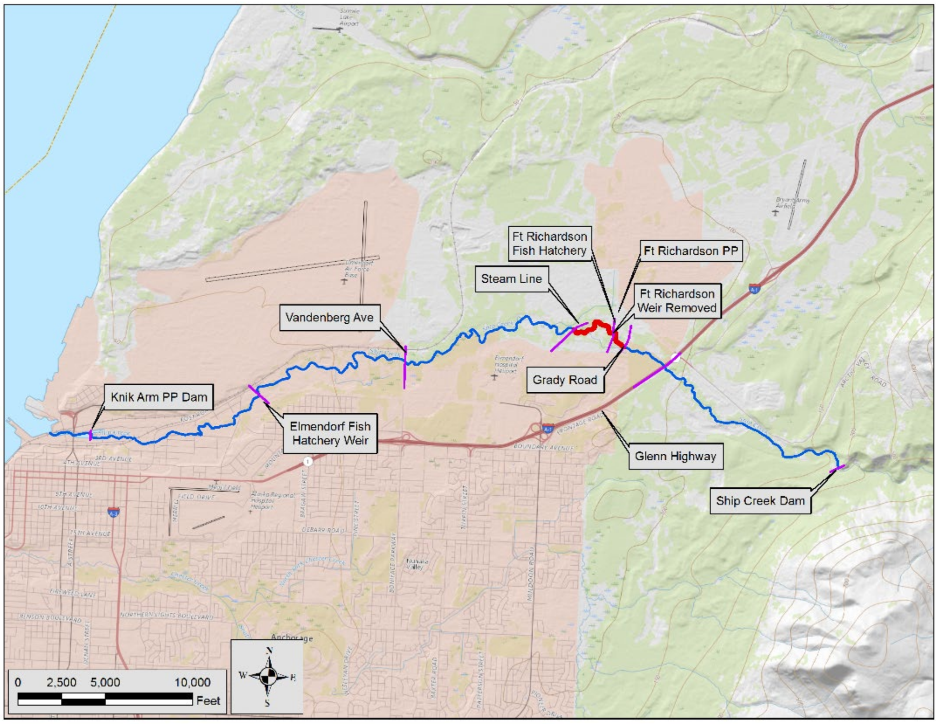
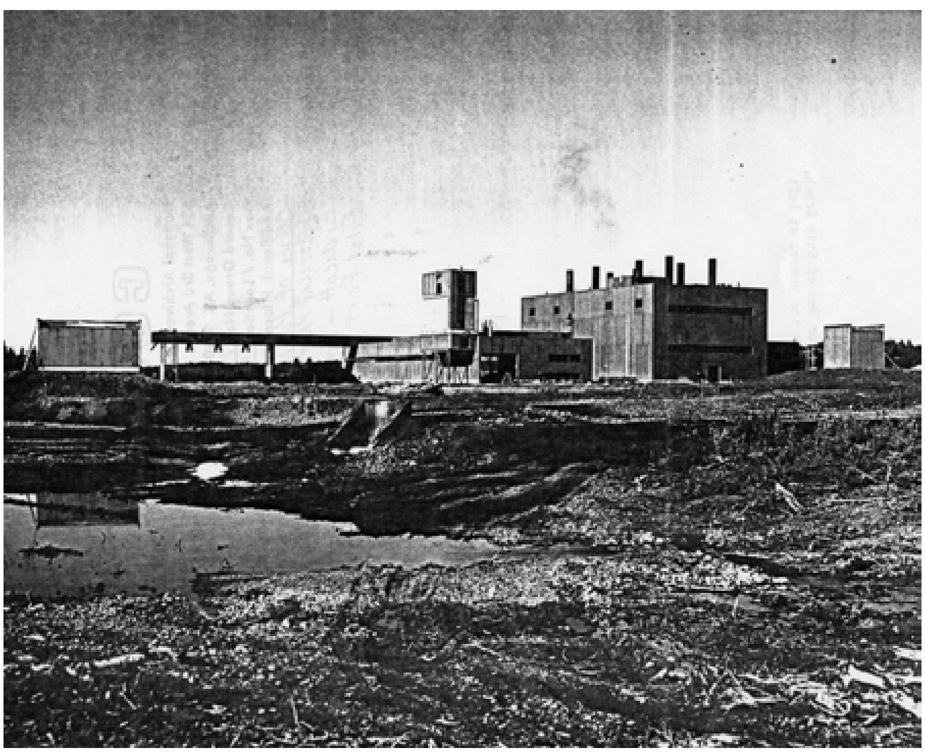


Figure 3. A 1952 photo of the new Fort Richardson Power Plant. The photo was taken from the bed of Ship Creek with intake pipes in the gravel at left foreground (Waddell 2003).



3 Ice-Affected Flooding

The rough limits of the *flood-prone reach* of Ship Creek are Grady Road Bridge and the steam-line crossing (see Figure 4). This reach contains the Fort Richardson Fish Hatchery (no longer used), the Fort Richardson Power Plant (decommissioned), and the Fort Richardson Power Plant small dam (now removed). There are also several occupied residences located at the Fort Richardson Fish Hatchery.

Figure 4. Flood-prone reach (*thick blue*) on Ship Creek.

While most of the flooding occurs in the flood-prone reach, there are also some anecdotal reports of flooding immediately upstream of Grady Road Bridge. These reports described Ship Creek flood waters advancing along the sides of Grady Road to the north and the south. Buildings at the Fort Richardson Fish Hatchery (Figure 5) have been inundated in the past. Hatchery Drive, the approach road to the Fort Richardson Fish Hatchery (Figure 6), has also been flooded. Access to the hatchery is impeded when flood waters cross the road, preventing safety vehicles from reaching the hatchery area. The first reported flooding at the fish hatchery occurred in the winter of 2004 (Andrea Tesch, ADF&G employee and Fort Richardson Fish Hatchery resident, pers. comm., January 2017). Significant flooding of the Fort Richardson Fish Hatchery was also reported for the winters of 2005–06 and 2016–17.

Figure 5. Inundation of buildings at the Fort Richardson Fish Hatchery.
(Image by Andrea Tesch.)

Figure 6. Flooding across the Fort Richardson Fish Hatchery Access Road.
(Image by Andrea Tesch.)

Figure 7 clearly shows the impact of ice on the water levels of Ship Creek. The three images in Figure 7 were taken in November and December of 2016 at the same location on Ship Creek in the flood-prone reach. This location is several hundred feet downstream of Grady Road Bridge (seen in the distance) looking upstream. The location of an old, disused well casing is marked by a yellow arrow in each image. The well casing stands vertically upright and extends approximately 6 ft above the bed of the creek. In the first image, taken on 16 November 2016, there is minimal ice present. Ship Creek is largely open, and the well casing stands in several inches of water. In the second image, taken on 12 December 2016, the creek is largely ice covered. The water level in the creek has risen over 5 ft at this time. Ship Creek is entirely ice covered except for a small open-water channel down the center of the channel. The rise in water level is due entirely to the ice formation in Ship Creek as the flow in the creek has undoubtedly dropped between these dates. The final image was taken on 15 December 2016. Ship Creek had risen several more inches since 12 December.

The Fort Richardson Power Plant impacted flooding in the flood-prone reach while it was in operation, from 1952 through October 2003. The warm effluent produced by the plant suppressed ice production in the creek and prevented flooding in the flood-prone reach. There are reports of flooding upstream of the power-plant location where the warm effluent would not influence ice production. The warm effluent was also used to warm the well water flowing into the Fort Richardson Fish Hatchery. It is significant that the first report of ice-affected flooding of the fish hatchery occurred in 2004, immediately following the power-plant decommissioning.

A small dam was constructed in Ship Creek when the Fort Richardson Power Plant was built (Figure 8). The dam impounded Ship Creek flow to provide cooling water to the power plant. The dam was a single concrete structure about 5 ft high by 80 ft wide that operated on a run-of-the-river basis (Inter-Fluve, Inc., 2007). After the power plant was decommissioned in 2003, the weir was no longer needed, but it was not removed until 2015. There is no clear picture of the impact of the dam on ice formation in Ship Creek and the subsequent flooding. A report on fish passage improvements for Ship Creek suggested that removing the dam would improve ice transport (Inter-Fluve, Inc., 2007). However, in a steep channel like Ship Creek, ice transport is not an important issue, as section 5 will discuss. In any case, ice-affected flooding occurred in winters before and after the dam was removed. This suggests that the dam did not have a significant impact on the ice-formation process.

Figure 7. Increase in water level caused by ice formation.

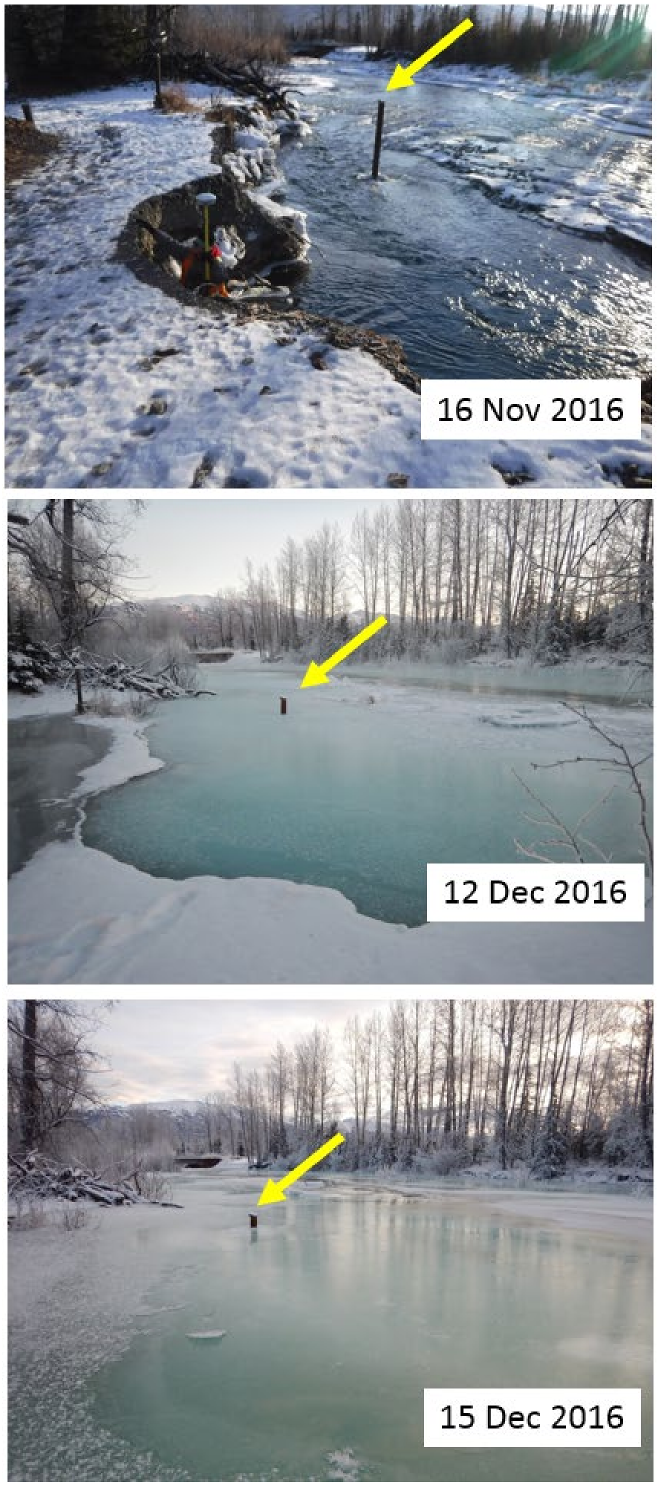


Figure 8. Small dam for Fort Richardson Power Plant (2007–10). (Image by Andrea Tesch.)

All reports and observations of flooding on Ship Creek consistently state that flooding occurs only during the ice-formation period. Flooding on Ship Creek has many similarities to flooding caused by *freeze-up ice jams* (USACE 2006). Similar to a freeze-up jam, flooding on Ship Creek occurs during periods of frigid air temperatures and declining stream discharge and results from blockage of the channel flow area by ice. There are no reports of flooding during spring breakup, as often occurs in Alaska. Observations suggest that the ice in Ship Creek downstream of the Ship Creek Dam melts out in the spring before the large snowmelt flows in the Chugach Mountains commence. As a result, the increased flow due to snowmelt does not encounter any channel ice below the Ship Creek Dam, and ice-affected flooding does not usually occur in the spring.

The flooding of the fish hatchery in the winters of 2005–06 and 2016–17 was relieved by mechanical removal. This was also effective in preventing flooding in the other years. For mechanical removal, bulldozers operate in the Ship Creek channel. Typically, the equipment operates in the reach between Grady Road Bridge and the steam-line crossing. There are two main objectives of mechanical removal. The first is removal of anchor ice and ice dams from the Ship Creek channel bed to increase the flow area of the channel and to lower the water levels. This is accomplished by driving a bulldozer in the channel in the upstream direction, with the dozer blade just above the channel bed (Figure 9). This procedure was followed on 13 January 2017 and was very effective in removing ice from the channel bed. The channel flow carried the removed ice downstream. This operation caused the water levels in Ship Creek to drop significantly. The second objective of mechanical removal is to break up and remove the surface-ice cover to provide room for the ice removed from upstream to deposit without raising the creek water levels (Figure 10 and Figure 11). This operation places much more stress on the dozers than simply removing ice from the channel bottom. Figure 12 shows the ice cover of Ship Creek after fracturing.

Figure 9. Bulldozer removing ice from the channel bed (January 2017).

Figure 10. Breaking up the surface-ice cover (2007–10). (Image by Andrea Tesch.)

Figure 11. Breaking up the surface-ice cover (January 2017).

Figure 12. Ship Creek stationary ice cover after fracturing by a bulldozer.

4 Ship Creek Watershed

4.1 Overview

Ship Creek has its headwaters in the Chugach Mountains and its outlet in Cook Inlet near downtown Anchorage, Alaska (Figure 1). The Chugach Mountains are underlain by bedrock, which is widely exposed at the land surface. The rocks that form the Chugach Mountains—greenstone, graywacke, slate, argillite, and limestone—are exposed in the canyon walls of Ship Creek where it flows from the mountains (Cederstrom et al. 1964). In its final 10 miles, after emerging from the mountains, Ship Creek flows over unconsolidated deposits, chiefly glacial drift laid down beneath or in front of the great glaciers that flowed into and along the lowland during the Pleistocene Ice Age. This study focuses on the final 10 miles of Ship Creek.

The area of the Ship Creek watershed is 127.6 square miles with about 89 square miles located in the Chugach Mountains. The annual maximum flow in Ship Creek generally occurs in June, reaching about 480 cfs on average. The flows in Ship Creek decrease throughout the winter, reaching a minimum of about 25 cfs in late March.

The most significant hydraulic structure on Ship Creek is the Ship Creek Dam, located at the immediate edge of the Chugach Mountains (shown in Figure 1). The Ship Creek Dam is the upstream limit of the study reach of this project. This concrete dam was constructed between 1952 and 1954 to replace a previous wooden structure. It is a reinforced concrete gravity structure, 50 ft above the stream bed and 80 ft long. It has a crest width of 8 ft at an elevation 545 ft above sea level and a base width of approximately 45 ft. The dam has a 40 ft wide Ogee Spillway at the right-descending abutment. The dam is a run-of-the-river operation that supplies water to JBER. The original design capacity of the dam reservoir was 27 acre-feet (Weston Solutions 2013).

After Ship Creek leaves the Chugach Mountains, it drops approximately 500 ft in elevation in 10 miles before reaching the Knik Arm of Cook Inlet. The majority of the length of Ship Creek in this section is contained within JBER and the JBER cantonment. The lower 2 miles of Ship Creek flow through Anchorage and can be influenced by the tides of Knik Arm. There are two control structures located on the lower part of Ship Creek. The Knik Arm Power Plant Dam is a gated structure located near the mouth of the creek. ADF&G operates the dam. The second structure is a closely spaced pair of steel sheet piling weirs located approximately 2 miles upstream at the William Jack Hernandez Sport Fish Hatchery. The weirs have a combined drop of about 12 ft. The weirs were originally constructed to supply cooling water to the Elmendorf Air Force Base Power Plant. There are no other structures currently located in the creek. In the past, the water from Ship Creek was also an important source of cooling water for the Fort Richardson Power Plant and water supply for Fort Richardson Fish Hatchery located immediately adjacent to the plant. The Fort Richardson Power Plant closed in 2003, and the Elmendorf Power Plant closed in 2006. The Fort Richardson Fish Hatchery closed in 2014. A small weir located at the Fort Richardson plant was removed in January of 2015.

In the upper portion of the study reach, from the Ship Creek Dam to approximately Grady Road Bridge, Ship Creek is a losing stream with water leaving the stream channel and flowing vertically downward into the unconsolidated deposits. In its lower portion, from about 1 mile downstream of Vandenberg Avenue Bridge to Knik Arm, Ship Creek is a gaining stream with groundwater entering the stream channel (Weeks 1970). This alternating outflow and inflow of water into Ship Creek has a significant impact on the distribution of ice in the creek channel.

The outflow from Ship Creek downward into the unconsolidated deposits is an important source of groundwater recharge (Cederstrom et al. 1964; Hunter et al. 2000). A shallow, unconfined aquifer lies beneath much of the watershed of the study reach. This aquifer is underlain by a relatively impervious, fine-grained layer composed of mud and diamicton. A second, deeper confined aquifer lies beneath this shallow aquifer and is also underlain by a layer of mud and diamicton (Hunter et al. 2000). The glacial deposits beneath the Ship Creek are “extremely variable due to the dynamic environment in which they [were] formed” (Weston Solutions 2015), and the areal extents and connections between the two aquifers have not been completely mapped out.

The importance of the aquifers to JBER and Anchorage has waxed and waned over the years. A large number of shallow and deep wells were drilled in JBER near Ship Creek beginning in the 1950s. These include 3 large-diameter water supply wells, all 145 ft deep or deeper, installed in the confined aquifer in 1956; and 22 wells installed in the unconfined aquifer and 2 wells in the confined aquifer for the Fort Richardson Fish

Hatchery in the 1970s and 1980s. None of these wells are currently operational as described in section 4.4.3 below. There are four currently operational wells in JBER near Ship Creek, three wells installed in the confined aquifer provide cooling water for the Elmendorf Air Force Base Hospital, and one well installed in the confined aquifer provides water for the Anchorage Water and Wastewater Utility (U.S. Army Garrison, Alaska 2005).

4.2 Previous reports

There are a number of reports on Ship Creek, the Ship Creek watershed, and the groundwater conditions of the Ship Creek watershed. This reflects the interesting geologic location of Ship Creek, the historical importance of groundwater to the city of Anchorage and JBER, and the importance of Ship Creek for water supply to JBER. Appendix A provides a bibliography of these reports. The topic areas covered are fish passage, geology, groundwater, history, Ship Creek Dam, Ship Creek hydrology, and wells.

4.3 Weather

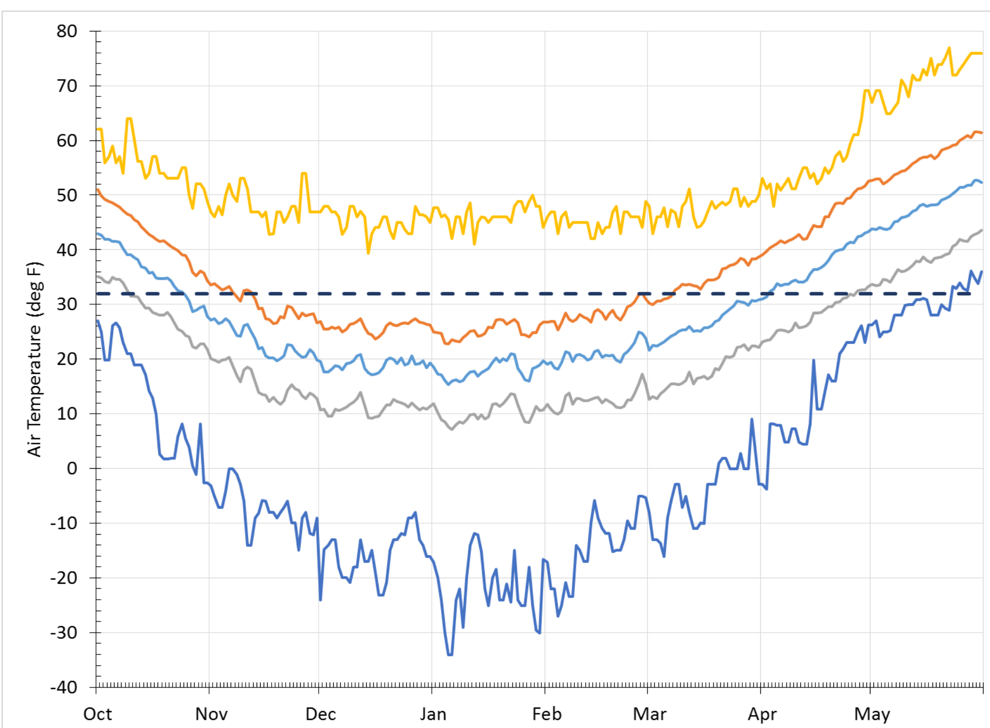
The study reach of Ship Creek is located in the Transitional Climate Zone between the relatively warm Maritime Zone along the Alaskan coast and the relatively cold Continental Zone, which covers the interior of most of Alaska. The portion of Ship Creek contained in the Chugach Mountains, upstream of the study reach, is considered part of the Continental Zone (Zenone and Anderson 1978). While Anchorage winter air temperatures are consistently below freezing, the low temperatures are sometimes interrupted by brief warm periods. These warm periods are often caused by “chinook” winds, which result from low pressure systems in the Gulf of Alaska. The low-pressure systems pull up warm air from the Pacific and raise temperatures dramatically. As a result, daily winter temperatures in Anchorage can display a large variability, larger than other times of year.

Table 2 lists monthly normals for precipitation, temperature, and snowfall for Anchorage, Alaska. Anchorage receives approximately 16.6 in. of precipitation each year, with over half falling in July through October. A normal winter has about 74.5 in. of snowfall. Figure 13 shows the statistics for daily maximum and minimum air temperatures for Anchorage. The daily average air temperature typically falls below freezing (32°F) in late October and remains below freezing until late March (Figure 13). The daily average minimums are typically about 20°F less than the daily average temperature, reaching single digits by the middle of October. Extreme low temperatures can be below −10°F from early December through the end of February and reach below −30°F in January (Figure 13).

Table 2. Monthly normals for Anchorage, AK (National Weather Service 2018).

Month	Total Precipitation Normal (in.)	Mean Max Temperature Normal (°F)	Mean Min Temperature Normal (°F)	Mean Avg. Temperature Normal (°F)	Total Snowfall Normal (in.)
January	0.73	23.1	11.1	17.1	11.3
February	0.72	26.6	13.8	20.2	10.9
March	0.60	33.9	19.2	26.6	9.9
April	0.47	44.5	29.1	36.8	4.0
May	0.72	56.0	39.6	47.8	0.3
June	0.97	62.8	47.7	55.2	0.0
July	1.83	65.4	52.2	58.8	0.0
August	3.25	63.5	50.0	56.7	0.0
September	2.99	55.1	42.0	48.6	0.4
October	2.03	40.5	29.1	34.8	7.9
November	1.16	27.8	16.6	22.2	13.1
December	1.11	24.8	13.2	19.0	16.7

Figure 13. Daily air-temperature statistics for October through May. Shown are the average daily maximum (*orange*), the daily average (*light blue*), the average daily minimum (*gray*), the extreme daily maximum (*yellow*), and the extreme daily minimum (*dark blue*) over the period of record. The dotted line indicates the freezing temperature (32°F).



4.4 Hydrology

4.4.1 Surface water

The primary source of information on flow in Ship Creek is from U.S. Geological Survey (USGS) gage 15276000, which has the official name of "Ship Creek near Anchorage, AK" (USGS 2017). This gage, located immediately downstream of the Ship Creek Dam, has been recording stage and flow in Ship Creek since 1 October 1946. In recent years, water temperature and water-surface-elevation (stage) data has been collected at this location as well. Other USGS gages were installed in previous years on Ship Creek downstream of the present gage site (Table 3). These gages have since been removed.

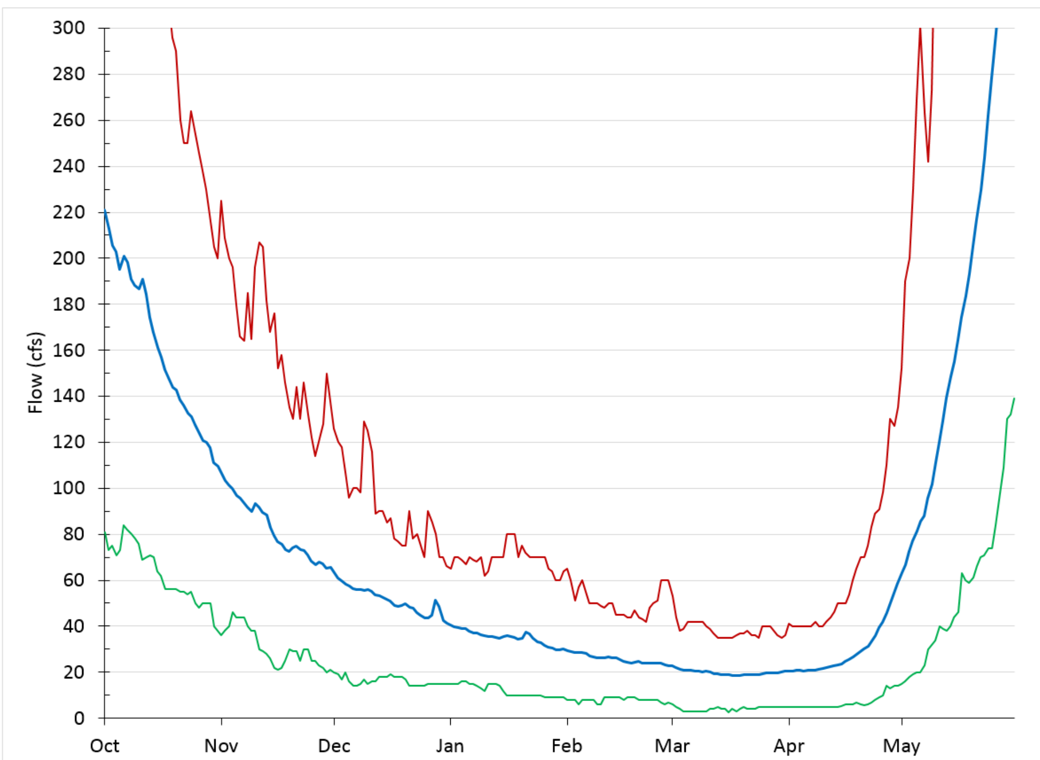
Table 3. USGS Gages on Ship Creek

	DA	Elev.	Start	End
USGS 15276000 SHIP C NR ANCHORAGE AK	89.6	490	1946-10-01	Present
USGS 15276570 SHIP C BL POWER PLANT AT ELMENDORF AFB AK	122	80	1970-10-01	1981-01-31
USGS 15276320 SHIP C BL FISH HATCHERY NR ANCHORAGE AK	104.6	225	2002-10-01	2004-09-30
USGS 15276500 SHIP CREEK AT ELMENDORF AIR FORCE BASE NEAR ANCHORAGE	113	–	1963	1971

In an average year, the maximum discharge in the study reach of Ship Creek occurs in early to mid-June. The average maximum flow in Ship Creek is approximately 480 cfs and occurs on 16 June. These maximum flows result from snowmelt in the Chugach Mountains combined with the low to moderate rainfall that can occur at that time. However, the maximum instantaneous discharges have been recorded in August and September, the months of maximum rainfall. (The all-time maximum daily average discharge was 2090 cfs, which was recorded on 23 September 2012.)

The discharge in the Creek tends to decline starting in October and continues to decline consistently throughout the winter until the end of March when it reaches a flow of less than 20 cfs. This *recession flow* is typically seen in creeks, rivers, and streams where the air temperatures are consistently below freezing. During this cold weather, no liquid precipitation falls and no snowmelt occurs; so all the discharge is the result of groundwater drainage. Recession flow represents the groundwater supply to Ship Creek slowly draining out over the winter. The recession flow of Ship Creek during the winter months is very consistent, as seen in Figure 14. The short warming periods during the winter associated with the "chinook" winds and other causes generally have little effect on the flow of Ship Creek. This is likely because the warming periods are too brief to cause enough snowmelt and to increase the flow of the Creek. The flow in the Creek starts to increase at the end of March and increases very steadily through April and May until the peak in June. This yearly consistency in the springtime flow increase reflects the consistency in the increase of sunlight that occurs in Alaska during the spring. Sunlight is a major component of the heat transfer causing snowmelt in the Chugach Mountains, leading to the increase in flow.

Figure 14. Ship Creek flows (the minimum, average, and maximum flows recorded on each day of the winter season, 1 October through 31 May).



As mentioned previously, the Ship Creek Dam is located at the upstream end of the study reach. The dam is a run-of-the-river operation, which means that it does not affect the flow in Ship Creek directly. The water supply for JBER is withdrawn from the reservoir located upstream of the dam. The withdrawals are taken on an as-needed basis, and there is no convenient record of the minute-by-minute withdrawal rate. However, a record of the total daily withdrawal from Ship Creek is maintained. These withdrawals can reduce the discharge in the Creek downstream of the dam. Given that the USGS gage is also located downstream of the dam, it is not possible to estimate the withdrawals from observed discharge records. In any case, the withdrawals are relatively modest when compared to the total flow in Ship Creek. From 1 October 2015 through 30 November 2016, JBER received 90.8% of its water from Ship Creek, 9.05% from water wells located in JBER, and 0.15% from the Anchorage Water and Wastewater Utility. A total of 121×10^6 cu ft were withdrawn from the Ship Creek Dam reservoir during this period at an average withdrawal rate of 3.3 cfs.

The portion of Ship Creek from immediately below the Ship Creek Dam to the USGS gage at Elmendorf Air Force Base (this gage was located just downstream of Vandenberg Avenue Bridge and was removed in 1971) has long been recognized as a *losing reach* of Ship Creek (Weeks 1970; Waller 1964). This was determined by comparing the discharge at the two USGS stations when both were operational. Along this reach, flow from Ship Creek seeps downwards into the ground and is lost from the creek. Estimates of the total seepage flow along this reach range from 7.7 cfs up to 25 cfs (Hunter et al. 2000; Weeks 1970; Waller 1964). Weeks (1970) also recognized that part of this loss returns to Ship Creek below the Elmendorf Air Force Base gaging station. This means that this reach below the Elmendorf gage is a *gaining reach*. His measurements indicated that the mean annual gain was about 22 cfs and possibly more flowing back into Ship Creek in this reach. He compared the inflow rate to what would be available from precipitation falling on the lower portion of the watershed and noted that only about half of this inflow could be the result of precipitation. He concluded that at least 11 cfs must result from groundwater recharge from above the Elmendorf gaging station.

4.4.2 Channel characteristics

Ship Creek is hydraulically steep, with a substrate of gravel, cobbles, and small boulders throughout most of its length. Sand is also visible on the bed near the downstream end of the creek. The channel profile continuously drops from the Ship Creek Dam down to Knik Arm (Figure 15). Ship Creek is quite steep immediately downstream of the Ship Creek Dam, with a bed slope of 2%. The slope declines in the downstream direction, reaching just under 1% by the Glenn Highway Bridge and 0.7% at the steam-line crossing (Figure 16). This range of slopes ensures that the flow velocity is high, the channel depths are relatively small, and the turbulent mixing is large. These channel conditions have a profound impact on the ice-formation process discussed in section 5.

Figure 15. Ship Creek bed profile.

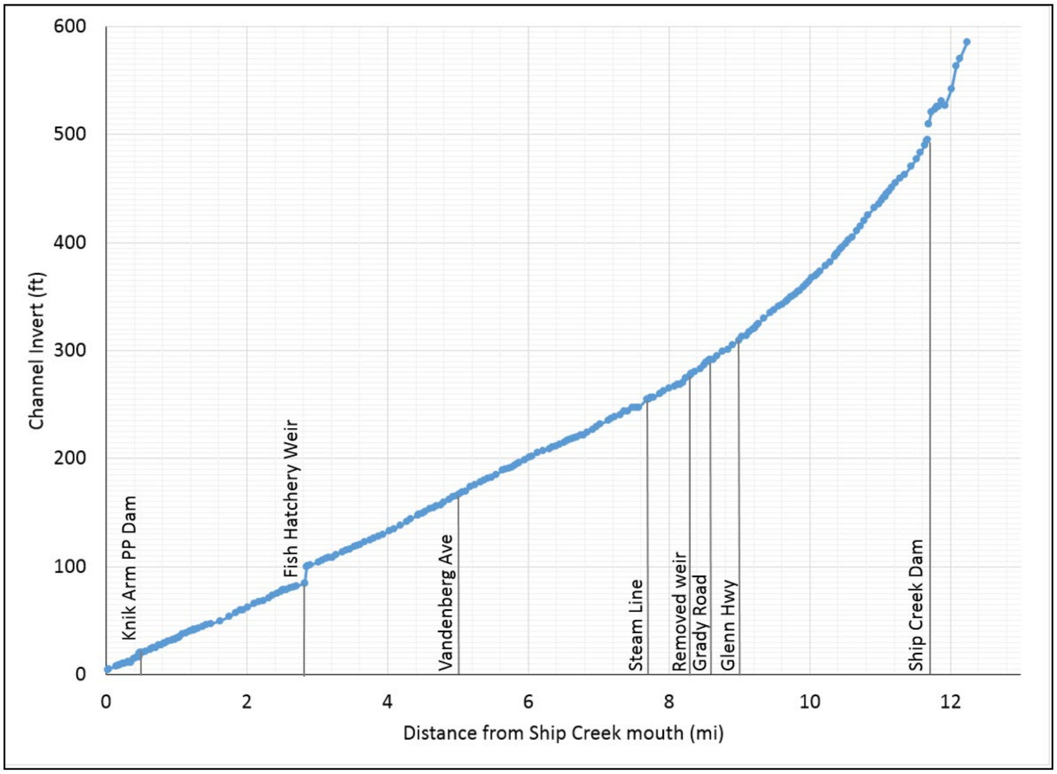
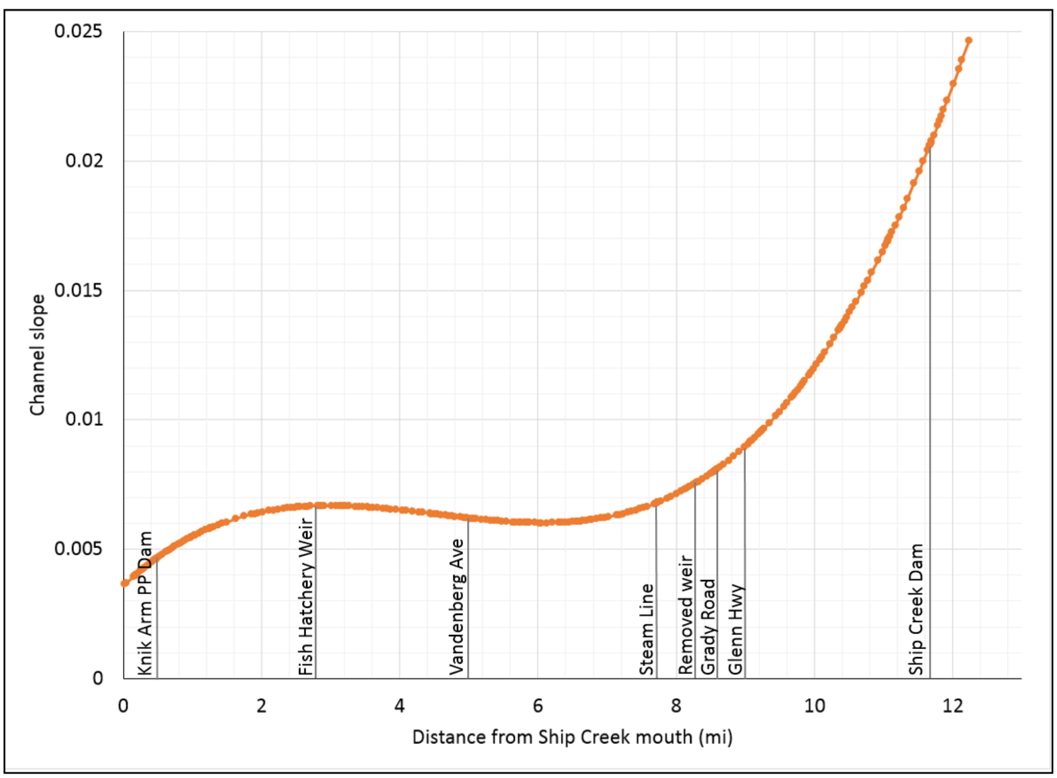


Figure 16. Ship Creek bed slope profile.

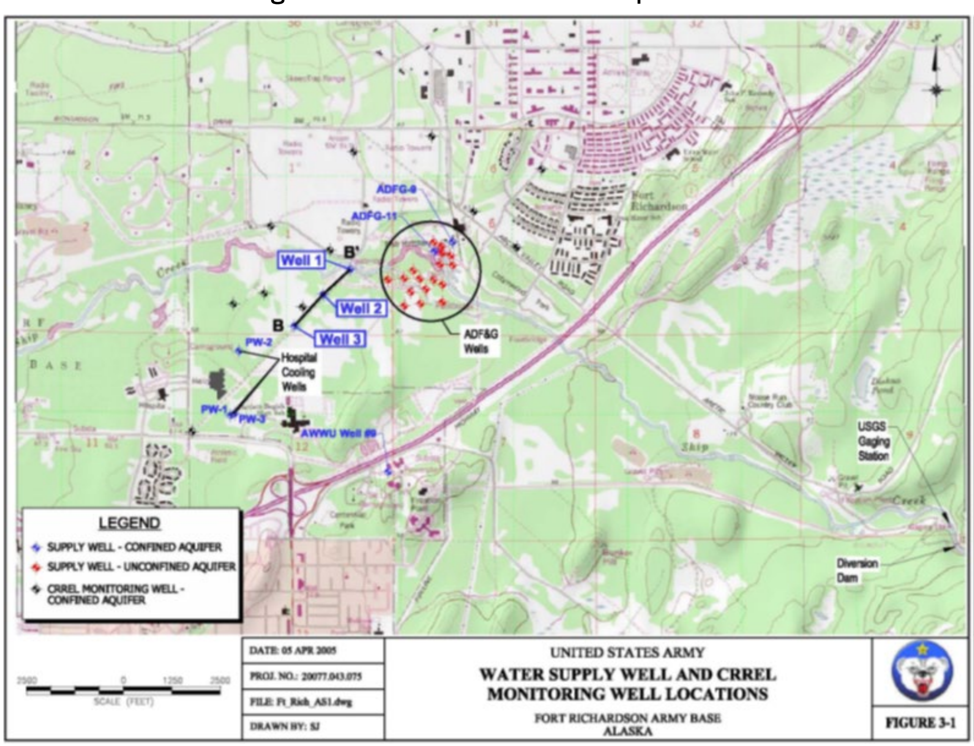


4.4.3 Groundwater development along Ship Creek

Groundwater has long been an important resource for Anchorage and JBER (Cederstrom et al. 1964; Barnwell et al. 1972; Anderson 1977; Zenone and Anderson 1978; Hunter et al. 2000). A number of wells have been installed in JBER close to Ship Creek. It is worth reviewing the currently existing wells as application of well water into Ship Creek is one potential flood mitigation option.

As mentioned in section 4.1, both a shallow, unconfined aquifer and a deep, confined aquifer underlay much of the Ship Creek watershed located on JBER. Wells installed in JBER that pump water from the unconfined aquifer are shallow wells with depths generally less than 50 ft. The flow rates from shallow wells range from 100 to 250 gpm. Wells designed to remove water from the confined aquifer are deep wells with depths greater than about 140 ft. Flow rates from deep wells are highly variable and range from 200 to 1200 gpm. Figure 17 shows the locations of the water wells near Ship Creek. There are three main groups of wells: Fort Richardson supply wells, ADF&G wells, and others. Data on the wells came largely from the *Final Aquifer Study Report* (U.S. Army Garrison, Alaska, 2005) and also from the State of Alaska Well Log Tracking System (WELTS) (Alaska Department of Natural Resources 2017).

Figure 17. Well locations near Ship Creek.



4.4.3.1 Fort Richardson supply wells

Table 4 provides data on the Fort Richardson supply wells. The U.S. Army Corps of Engineers (USACE) installed these three wells in 1956–57 for water supply. They draw water from the confined aquifer. The original flow rates were around 1200 gpm. In later years, Well 2 supplied water to Fort Richardson while Wells 1 and 3 supplied water to the ADF&G Fort Richardson Fish Hatchery. U.S. Army Garrison, Alaska (2005), reports a "steady decline" in production from Wells 1 and 3 in 2005. Well 3 was "disabled" in 2005 and has not operated since.

Table 4. Fort Richardson supply wells.

WELTS Log ID	Well Name	Total Depth (ft)	Static Water Level (ft)	Estimated Flow (gpm)	Created or Earliest Record	Last Used or Serviced
3423	Army Supply Well No. 1	162	37	1227	10/26/1956	No data
3422	Army Supply Well No. 2	166	24.7	1181 w/ drawdown of 64 ft	11/26/1956	No data
3424	Army Supply Well No. 3	145	31	1200 w/ drawdown of 62 ft	1/10/1957	March 2005

4.4.3.2 ADF&G wells

Water supply for the Fort Richardson Fish Hatchery was provided by 22 groundwater wells. These wells were shut down in 2014 when the Fort Richardson Fish Hatchery closed. There are three groups of ADF&G Wells. The ADF&G Old Well Field is located north of Ship Creek. Wells in this field were installed between 1971 and 1976 in the unconfined aquifer. Table 5 lists data on the Old Well Field. The ADF&G New Well Field is located south of Ship Creek. Wells in this field were installed between 1980 and 1982 in the unconfined aquifer. Table 6 lists data on the New Well Field. There are also two ADF&G Deep Wells near Ship Creek. These wells were installed in the confined aquifer. Table 7 lists data on the Deep Wells.

Figure 18 shows the production rates of the ADF&G well fields for 2006 through 2014 (A. Tesch, unpublished data, January 2017). These are the only years with data available. The production rate was fairly constant from 2006 through 2011. The average production rate for the New Well Field during this time was 2500 gpm, the Old Well Field was 855 gpm, and the Deep Wells 380 gpm. In 2011, the William Jack Hernandez Sport Fish Hatchery was opened, and fish production at the Fort Richardson Fish Hatchery began to decline. This resulted in a near constant decline in the well production after 2011. In 2014, the Fort Richardson Fish Hatchery closed, and the well fields were shut off. They have not been used since. Some electrical equipment has been removed, and the current condition of the well field is not known (A. Tesch, pers. comm.).

Table 5. ADF&G Old Well Field.

WELTS Log ID	Well Name	Total Depth (ft)	Static Water Level (ft)	Estimated Flow (gpm)	Created or Earliest Record	Last Used or Serviced
11690	ADFG-1	44	13	180	3/8/1971	11/2014
11691	ADFG-2	41	No data	230	3/25/1971	11/2014
11692	ADFG-3	43	17.75	80	4/1/1971	11/2014
11693	ADFG-4	41	16.33	180	5/4/1971	11/2014
11694	ADFG-5	30	13	100	9/1976	11/2014
11695	ADFG-6	30	15.42	150	9/1976	11/2014
13320	ADFG-7	33	9.8	180	No data	11/2014
11696	ADFG-8	27	9	70	9/1976	11/2014
13319	ADFG-10	89	No data	150	No data	11/2014

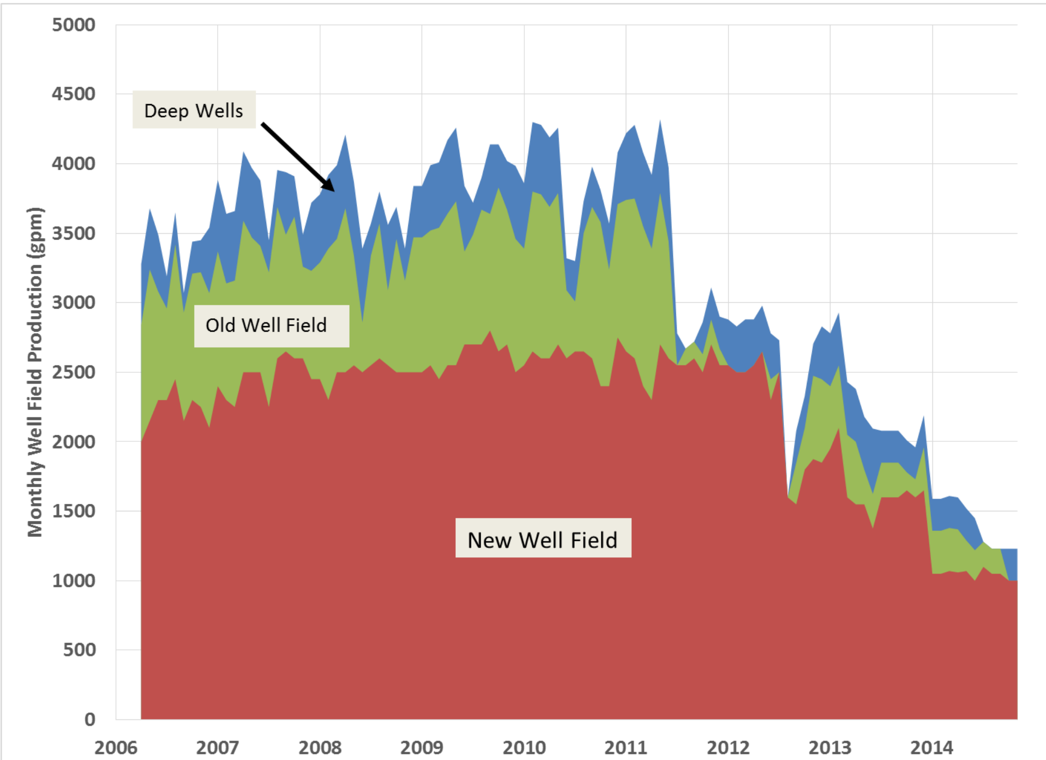
Table 6. ADF&G New Well Field.

WELTS Log ID	Well Name	Total Depth (ft)	Static Water Level (ft)	Estimated Flow (gpm)	Created or Earliest Record	Last Used or Serviced
13307	W-A	40.5	10.4	225	2/19/1980	11/2014
13308	W-B	42	12.4	250	2/19/1980	11/2014
13310	W-C	43	10.6	225	2/22/1980	11/2014
13311	W-D	50	7.4	175	1/12/1982	11/2014
13312	W-E	43	9.2	250	1/13/1982	11/2014
13321	W-F	49	8.0	No data	1/13/1982	11/2014
13314	W-G	23	8.4	130	1/14/1982	11/2014
13313	W-I	39	10.8	225	1/14/1982	11/2014
13316	W-J	43	11.0	175	1/14/1982	11/2014
13315	W-K	39	8.4	125	2/11/1982	11/2014
13317	W-N	50	8.7	200	2/23/1982	11/2014

Table 7. ADF&G Deep Wells.

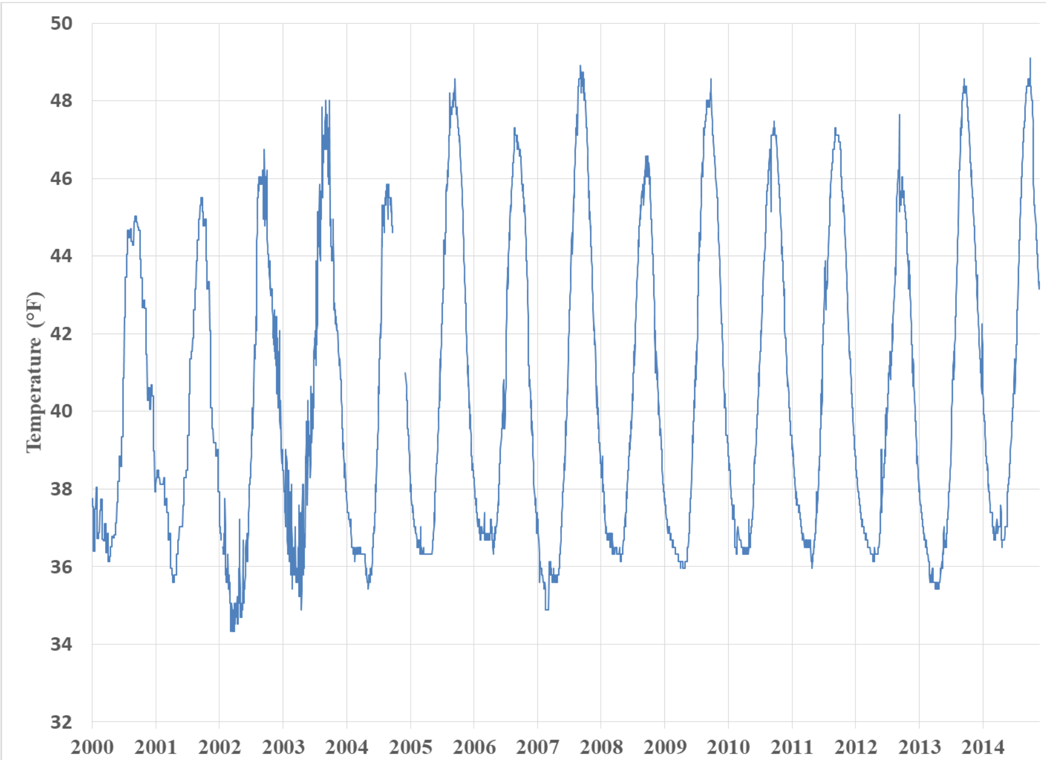
WELTS Log ID	Well Name	Total Depth (ft)	Static Water Level (ft)	Estimated Flow (gpm)	Created or Earliest Record	Last Used or Serviced
13318	ADFG-9	144	57	375	11/14/1983	11/2014
29947	ADFG-11	150.3	65.92	217	6/27/2003	11/2014

Figure 18. ADF&G well production 2006–14.



In addition to the production rates, the temperature of the groundwater is an important consideration when using well water to suppress ice production. Figure 19 shows the groundwater temperature, as recorded at the Fort Richardson Fish Hatchery (A. Tesch, unpublished data, January 2017). Shown is the temperature that resulted from combining the groundwater flow from all the ADF&G wells except the ADFG-11 Deep Well. ADFG-11 was plumbed into the fish hatchery separately. The combined inflow temperature reached has high as 48°F in the late summer and a low of 35.6°F in the winter. Information on individual well temperatures is not available, but generally the deep wells' water temperatures were higher than the shallow wells in winter and seldom dropped below 39°F (A. Tesch, pers. comm.).

Figure 19. Combined ADF&G well fields groundwater temperatures.



4.4.3.3 Other wells

There are a number of other wells located on JBER. Table 8 lists the closest wells to this section of Ship Creek. The wells labeled PW are used to supply water to the Elmendorf Air Force Base Hospital. The Anchorage Water and Wastewater Utility operates well AWWU-9. AWWU-9 supplies potable water supply for Anchorage and JBER on an "as-needed" basis. All the wells in Table 8 supply water from the deep, confined aquifer.

Table 8. Other wells.

WELTS Log ID	Well Name	Total Depth (ft)	Static Water Level (ft)	Estimated Flow (gpm)	Created or Earliest Record	Last Used or Serviced
12958	AWWU-9	298	33.3	1200	1967	In service
23211	PW-1	278	No data	500	11/9/1993	In service
24097	PW-2	267	113	850	2/24/1997	In service
24098	PW-3	225	106.3	450	2/25/1997	In service

5 Ice Formation in Ship Creek

There has not been any previous study of the ice conditions on Ship Creek despite the long history of ice-affected flooding. There are several interesting aspects to ice formation on Ship Creek that this section will address. These include the spatial distribution of ice formation along the creek; the annual variation in the length of the ice-formation period; the formation process itself, which occurs in a hydraulically steep channel; and why the flood-prone reach exists.

5.1 Spatial distribution of ice

One interesting feature of ice in Ship Creek is its discontinuous distribution: ice occurs only in one specific reach of Ship Creek (Figure 20). This section of Ship Creek is referred to as the *ice-formation reach*. The downstream limit of this reach is just downstream of Vandenberg Avenue Bridge, and it extends upstream to the Ship Creek Dam. It is not likely that ice passes over Ship Creek Dam, so all ice in the ice-formation reach is formed in this reach. This ice-formation reach closely matches the reach of Ship Creek where it is a losing stream. In this reach, water leaves the stream channel and flows vertically downward into the unconsolidated soil deposits beneath the stream (Weeks 1970). The *ice-free reach* is downstream of the ice-formation reach, from just downstream of Vandenberg Avenue Bridge to the creek’s outlet at Knik Arm. The ice-free reach generally remains largely open with some shore ice. This ice-free reach closely matches the gaining reach of Ship Creek where groundwater enters the stream channel (Weeks 1970). The heat contained in the groundwater entering Ship Creek in this reach is apparently sufficient to offset the heat loss from the creek surface to the frigid air and to prevent ice formation.

This study used satellite data to determine the extent of the ice-covered reaches in Ship Creek. Five satellite images were acquired by the WorldView satellite of Ship Creek in JBER during the winter of 2016–17. These images were acquired on 6 December 2016, 26 January 2017, 11 February 2017, 16 March 2017, and 15 April 2017. In addition, two WorldView satellite images of Ship Creek in JBER, requested by others during this period, became available for use by this study. These additional images were acquired by the WorldView satellite on 30 April 2017 and 15 May 2017. A search of satellite imagery of Ship Creek in JBER acquired before the winter of 2016–17 resulted in three additional WorldView images

(Acquired on 2 April 2014, 9 March 2015, and 3 April 2016) and one Google Earth image (14 April 2011). All the satellite imagery was examined to determine the spatial distribution of ice in Ship Creek on the acquisition dates. WorldView sensors are electro-optical systems collecting in the visible and near-infrared spectrum at a ground sampling resolution of 1.4 m. The satellite imagery was georeferenced using a high-resolution digital elevation model (5 m) and an existing high-resolution (0.5 m) pan-sharpened and orthocorrected satellite image as a reference file. The imagery was georeferenced using 12 ground control points that were matched with the reference files. The 12 ground control points were distributed across the images to reduce the residual errors and to minimize the total root-mean-squared error of the georeferenced images. The new georeferenced orthocorrected image files were then manually analyzed to determine the distribution of ice in Ship Creek.

Figure 20. Spatial distribution of ice formation on Ship Creek.

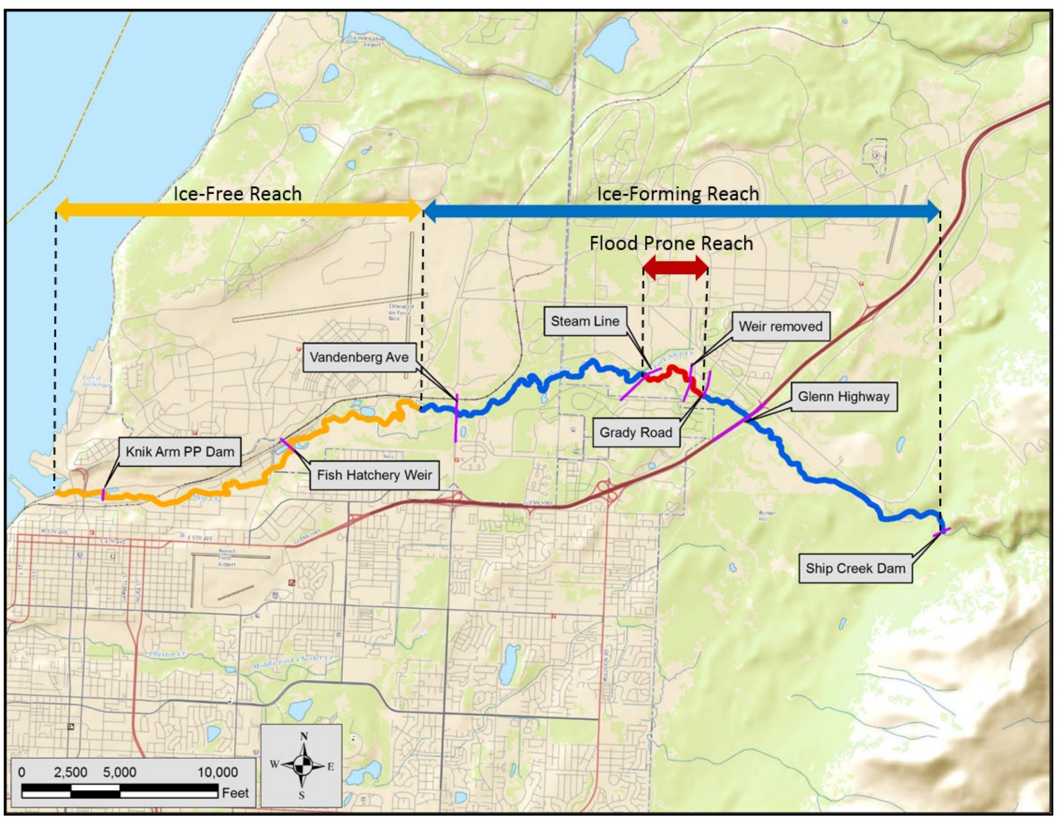


Figure 21 shows the results of the analysis of the ice distribution in Ship Creek. Each horizontal line is a schematic description of the distribution of ice along Ship Creek that was observed in the satellite imagery on the given date. The vertical order of the schematics corresponds to the day of winter of the acquisition without regard to the year that the data was acquired. The earliest day of winter that an image was acquired is at the top of the figure (6 December), and the latest day at the bottom (15 May). The downstream limit of Ship Creek at Knik Arm is on the left side of the figure, and the upstream limit at the Ship Creek Dam is on the right side. The vertical lines correspond to landmarks along Ship Creek: Knik Arm Dam, Vandenberg Avenue Bridge, the steam-line crossing, Grady Road Bridge, Glenn Highway Bridge, and the Ship Creek Dam. The imagery provides sufficient resolution to determine if ice is present but cannot provide much detail on the ice process. Table 9 describes the classification system.

The discontinuous distribution of ice on Ship Creek can be seen clearly in Figure 21. Continuous ice cover occurs only upstream or just below Vandenberg Avenue Bridge, as mentioned. Downstream of this point, only open water or open water with shore ice is present. A short reach of Ship Creek immediately upstream of Knik Arm can be ice covered. This reach is in the backwater formed by Knik Arm during high tides.

Figure 21. Ice observed in Ship Creek based on satellite imagery.

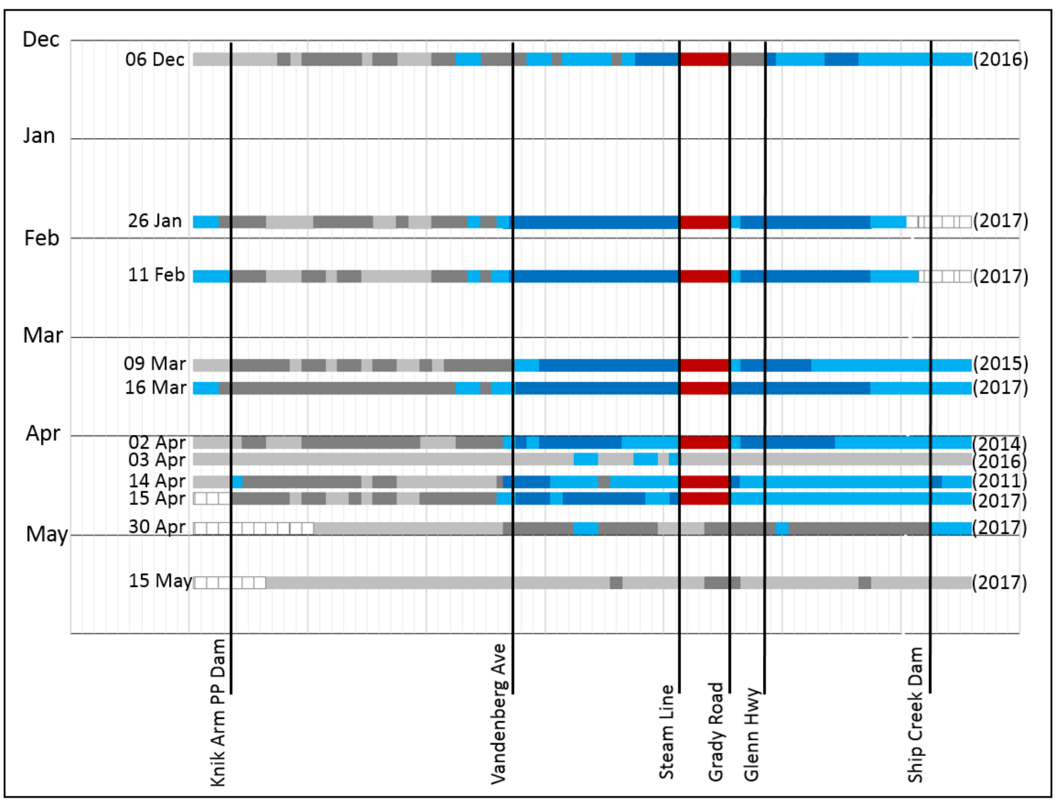


Table 9. Ice classification system.

CLASSIFICATION	SYMBOL	DESCRIPTION
Open Water		Only open-water surface visible. No ice.
Open Water with Shore Ice		All ice visible in the reach is along the shoreline with open water continuously along the center of the channel.
Ice Present with Open Water		Ice seen across the entire width of the channel. Open water visible only in separated, disconnected areas.
Ice Present		Only ice is present. No open water.
Ice Mechanically Removed		Ice and open water visible. Open water created by mechanical removal of ice.
Channel Not Visible		Channel not visible because it is out of the imagery acquired, or due to cloud cover, ground fog, or other reason.

5.2 Annual occurrence of ice

Ice typically is present in Ship Creek for 7 months each year from early October through April. The daily presence of ice can be determined from data published by the USGS for the gage “Ship Creek near Anchorage, AK” (Gage No 15276000), located immediately downstream of the Ship Creek Dam. The gage reading is not considered accurate when ice is present, and the flow rate is instead estimated by the USGS based on data from nearby watersheds and manual flow measurements made periodically throughout the winter. The days when the flow must be estimated are marked in the data record. The days when ice was present can therefore be determined by reviewing the data record and noting the dates when the flow was estimated. Figure 22 shows the days when ice was present at the USGS gage. It can be seen that ice was present each winter. Figure 23 shows the percentage of years with ice present for each day of the winter season. Ice is present for 90% of the years from the beginning of December through March.

Figure 22. Period each winter when ice was present at the USGS gage.

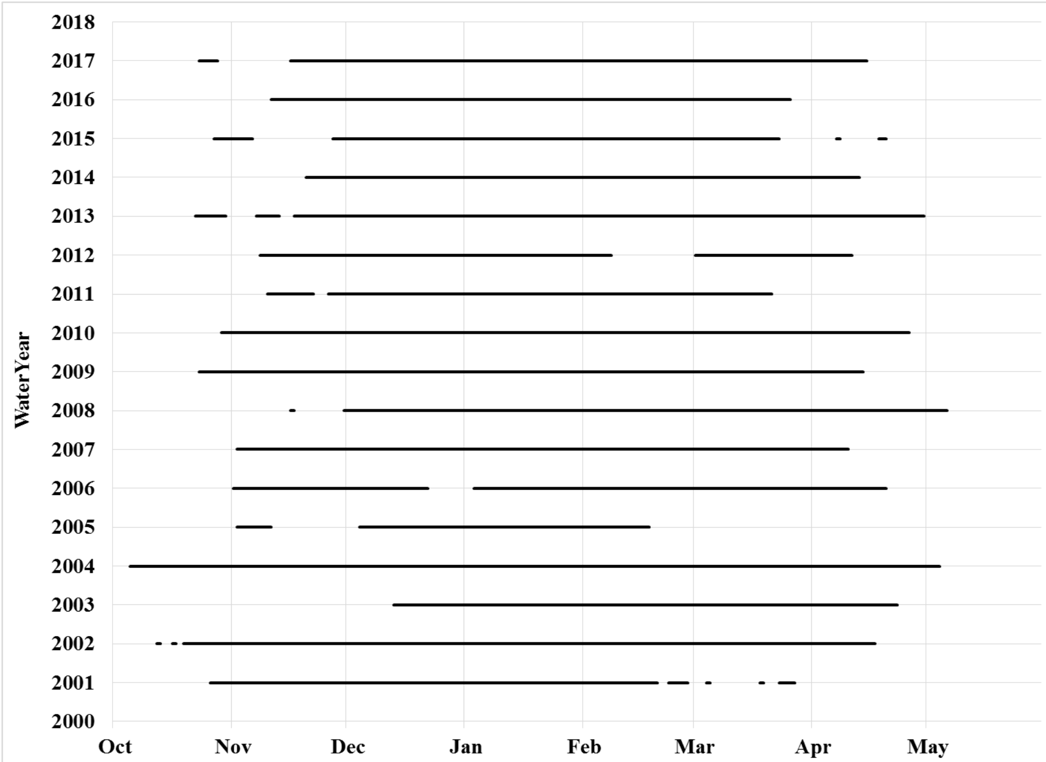


Figure 23. Percentage of winters (2001–17) with ice for each day of winter at the USGS gage.

5.3 Ice-formation process in Ship Creek outside of the flood-prone reach

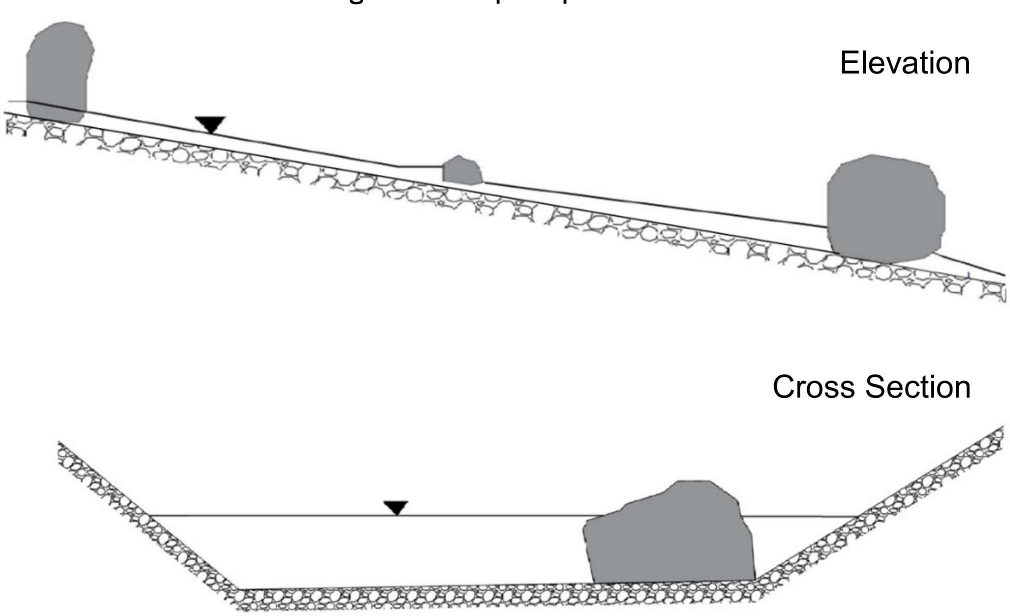
Significant ice formation in Ship Creek occurs only upstream of Vandenberg Avenue Bridge, as discussed previously. This ice-formation reach is hydraulically steep, with a substrate of gravel, cobbles, and small boulders. The ice-formation process in this reach is typical of ice formation in steep channels. Ice formation in hydraulically steep channels is a relatively new area of study. Several publications by Benoit Turcotte (Turcotte et al. 2011; Turcotte and Morse 2011; Turcotte et al. 2014a, 2014b) are the basis of our current understanding of ice formation in hydraulically steep channels.

The following description of the ice-formation process in Ship Creek is based on observations made over the 2016–17 winter. The description applies to most of the ice-formation reach but not to the flood-prone reach. This covers the portion of Ship Creek from the Ship Creek Dam downstream to Grady Road Bridge and from upstream of the steam-line crossing downstream to below Vandenberg Avenue Bridge. Section 5.4 will discuss ice formation in the flood-prone reach.

5.3.1 Open water

At the very beginning of the freeze-up process, there is no ice in the ice-formation reach of Ship Creek (Figure 24). The water temperature is just slightly above or at 32°F.

Figure 24. Step 1. Open water.



5.3.2 Anchor-ice formation

The freeze-up process begins when the air temperature drops below 32°F and heat transfer from the water surface to the atmosphere causes the water temperature to drop to 32°F and slightly below. In steep channels, the flow velocity of the water is too high to allow an ice cover to form at the surface of the water. The first ice formed, termed *frazil ice*, is small, individual ice crystals formed in turbulent supercooled water. The crystals, carried to the channel bottom by turbulent mixing, attach to the channel substrate to form *anchor ice*. The anchor ice builds up continuously on the bottom of the channel through the deposition of frazil and some growth through heat transfer from the anchor ice to the supercooled water. There is little or no water flow through the anchor ice, and the water must flow over the top surface of the anchor ice. Therefore, the buildup of anchor ice causes the water level in the creek to rise (Figure 25).

The buildup of anchor ice on the bottom of the Ship Creek channel occurs more-or-less simultaneously throughout the entire ice-formation reach, from Vandenberg Avenue Bridge up to the Ship Creek Dam. Frazil crystals formed in the turbulent flow are not carried far downstream before deposition on the bottom occurs, given the high levels of turbulent mixing and shallow flow depths (Figures 26 and 27).

Figure 25. Step 2. Anchor-ice formation.

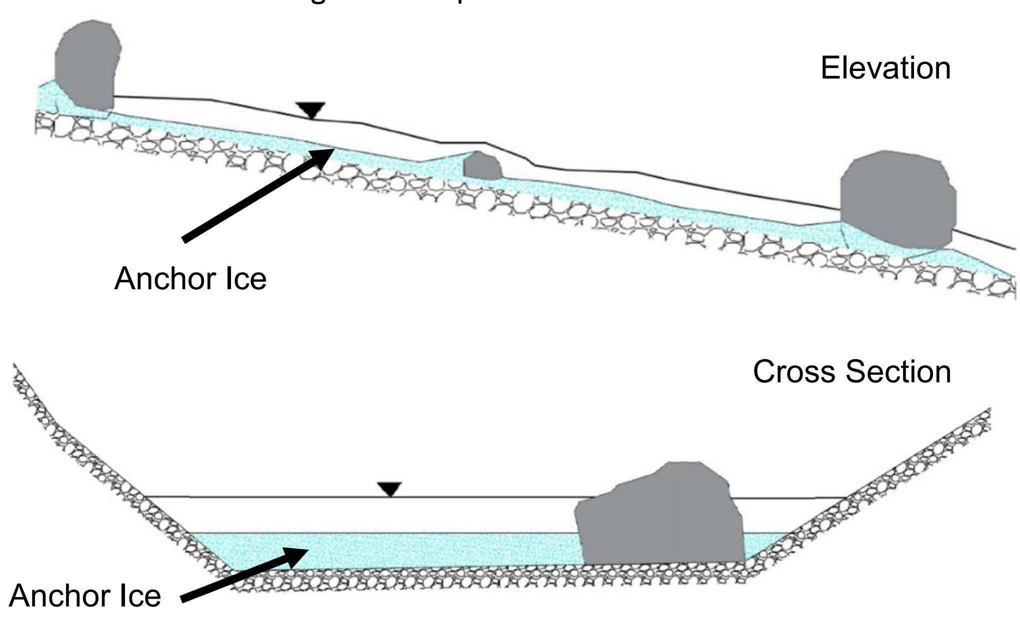
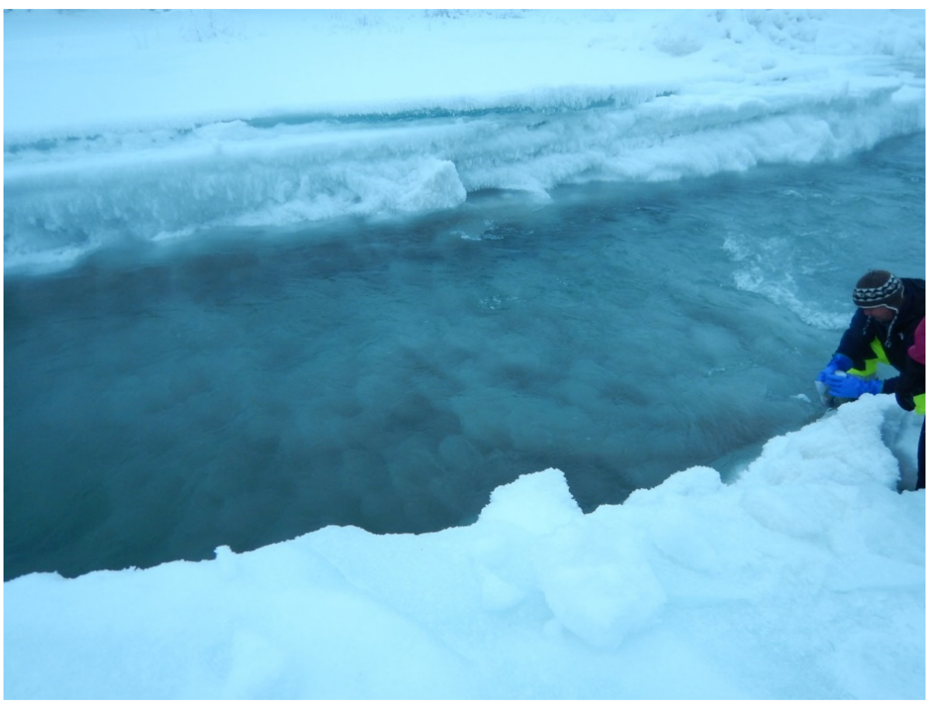


Figure 26. Anchor ice visible underwater (Ship Creek 16 November 2017).

Figure 27. Anchor ice visible underwater (Ship Creek 12 January 2017).



5.3.3 Ice-dam formation

Frazil ice is not deposited uniformly along the channel bottom. The deposition is augmented in certain areas, usually associated with large cobles or small boulders. In these areas, relatively large depositions occur, leading to the formation of frazil *ice dams* (Dubé et al. 2014) as shown in Figures 28 and 29. Ice dams can have a significant impact on the local flow conditions. They cause increased water levels immediately upstream of their location. The flow often passes over the top of the ice dams in weir-like flow, leading to the formation of *icings*. Icings occur when the water flowing over the ice weir freezes. This leads to continual vertical growth of the ice dams.

Figure 28. Step 3. Ice-dam formation.

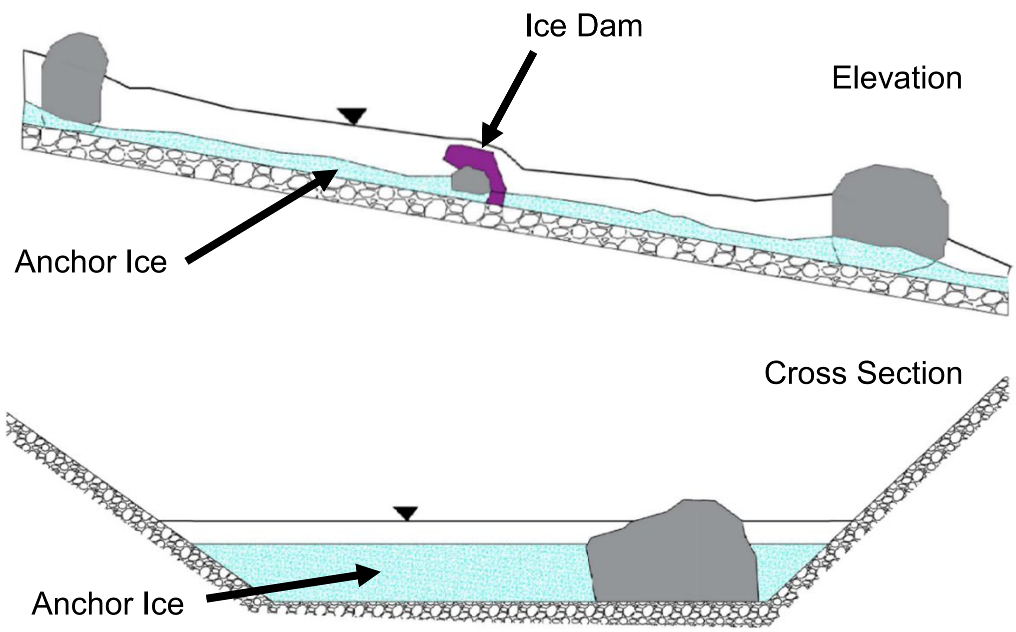


Figure 29. Ice dam and weir (Ship Creek 13 December 2016).

5.3.4 Stage increase with further ice formation

The formation of anchor ice, ice dams, ice weirs, and icings causes the water level in Ship Creek to rise (Figures 30 and 31). The rise is mitigated to a small degree by the flow recession—the daily decrease in Ship Creek discharge that occurs each winter. It is important to note that when the initial ice formation occurs, the wintertime discharge is at its maximum. The discharge in Ship Creek declines relatively slowly with time. The decline does not happen fast enough to reduce the water level rise caused by freeze-up to any significant degree.

The rise in the water level caused by the formation of anchor ice, ice dams, ice weirs, and icings tends to increase the channel flow area which in turn causes the flow velocity to decrease. Lower flow velocities tend to allow surface-ice covers to form. However, the water level can increase significantly before the flow velocity is reduced sufficiently to allow an ice cover to form spontaneously at the water surface. As long as open water remains in the channel, its exposure to the frigid air produces supercooled water, frazil ice, anchor ice, and ice dams. This ice formation continues to cause the water level to rise.

Figure 30. Step 4. Stage increase with further ice formation.

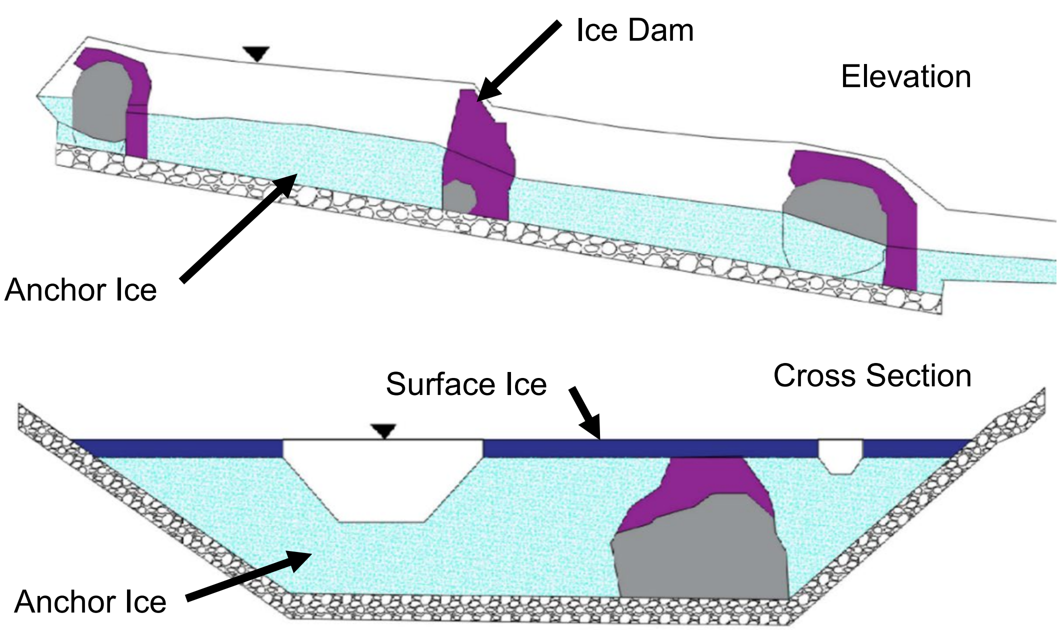
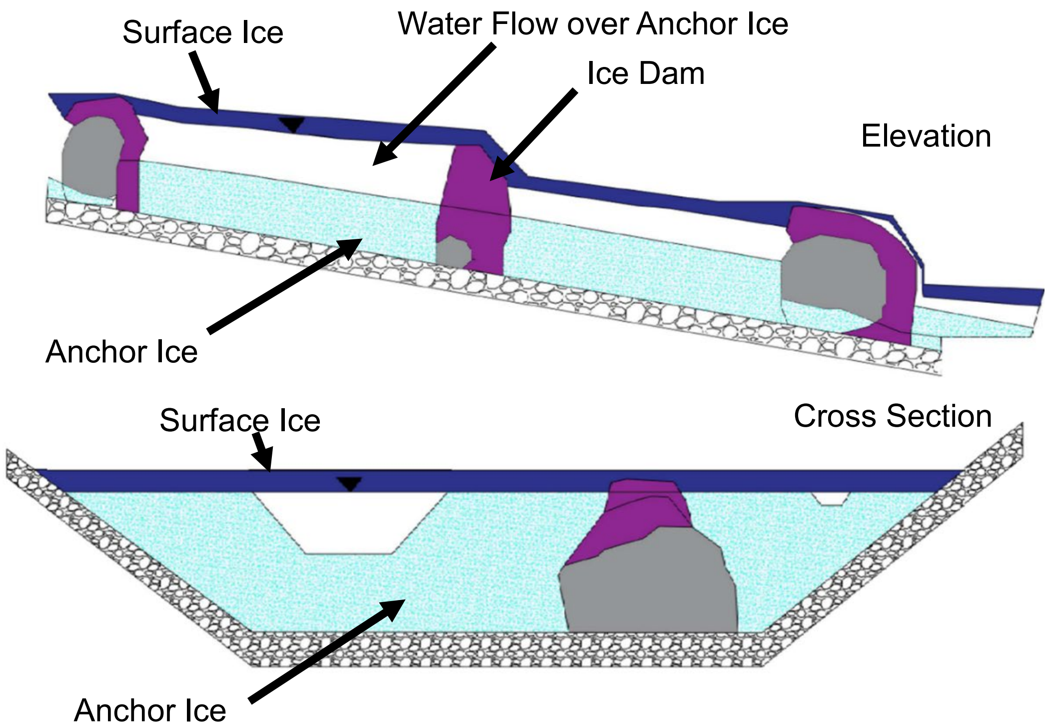


Figure 31. Large ice dam causing stage rise.

5.3.5 Formation of a complete surface-ice cover

An ice cover forms across the entire channel surface when the flow velocity has decreased sufficiently (Figure 32). At this point, there is no, or minimal, open water exposed to the frigid air. The MIAWL occurs at or near the time that the entire water surface of the Ship Creek channel becomes covered by ice.

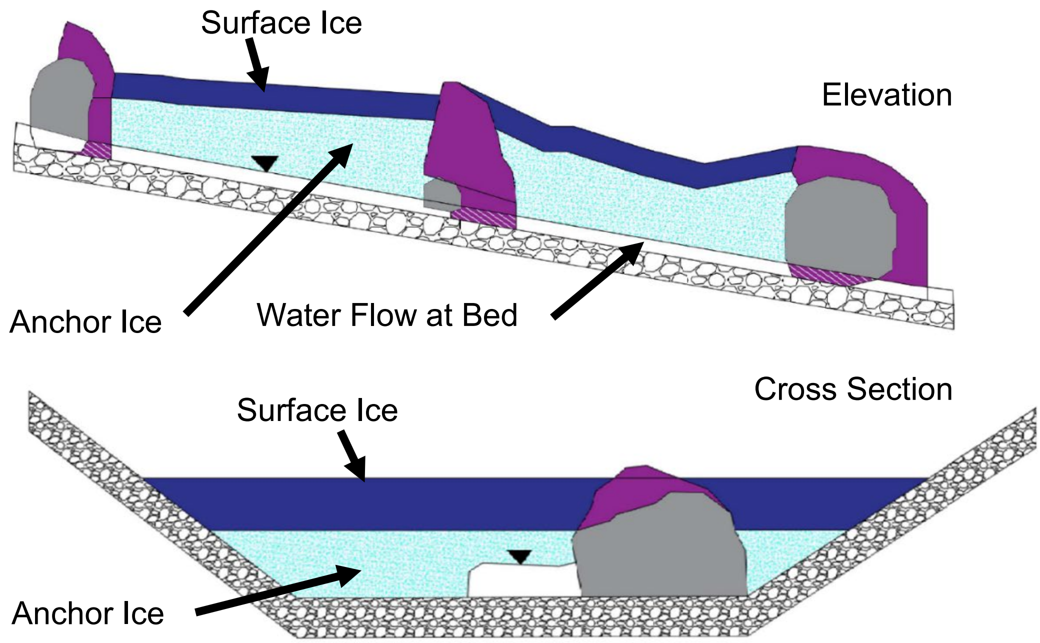
Figure 32. Step 5. Formation of a complete surface-ice cover.



5.3.6 Anchor-ice detachment and ice-dam breaching

Soon after the ice cover has formed over the entire channel surface, the water levels in Ship Creek drop dramatically. Apparently, the ice cover prevents the creation of supercooled water, which stops frazil ice formation and the growth of anchor ice and ice dams. In addition, two important events occur. The first is *detachment of the anchor ice* from the channel bottom. Observations have shown that that anchor ice remains attached to the channel bottom only if exposed to supercooled water. The reasons for this are not completely understood. When the production of supercooled water ceases, anchor ice becomes detached and floats up from the bottom. It is then held by buoyancy beneath the surface-ice cover. The second event is *breaching of the ice dams*. The ice dams breach when the water flow creates conduits through the dams. These conduits form when the flow is no longer supercooled. It is likely that the frictional heat of the flowing water increases the effective cross section of the conduits available to flow soon after they are formed. The net effect of the detachment of anchor ice and breaching of the ice dams is a significant drop in water levels (Figure 33). After this, the flowing water is confined to small passages located at the channel bottom and under the ice cover. The Ship Creek ice conditions do not significantly change until spring melt out occurs.

Figure 33. Step 6. Anchor-ice detachment and ice-dam breaching.



5.4 Flood-prone reach

Whether out-of-bank flooding occurs along a reach is a function of the geometry of the channel, specifically bank height, and the ability of the stream cross section to confine flow to the channel during freeze-up. If the top-of-bank elevations are higher than the MIAWL, then flooding does not occur. Observations during the winter of 2016–17 showed that the water level rise caused by ice formation was contained within the Ship Creek banks from the Ship Creek Dam downstream to Grady Road Bridge and from upstream of the steam-line crossing downstream to below Vandenberg Avenue Bridge. If the top-of-bank elevations are lower than the MIAWL, then flow is diverted out of the channel before the MIAWL is reached. Flow diversion leads to out-of-bank flooding, with the flood extent determined by the relative elevation of the overbank areas compared to the ice-affected water level. Observations during the winter of 2016–17 showed that the water level rise caused by ice exceeded the channel banks in the flood-prone reach, downstream of Grady Road Bridge to below the fish hatchery. This is the reach where flooding has occurred since 2004.

It is not possible at this time to estimate the MIAWL for a given channel section. Factors that could likely influence the MIAWL include the flow rate, channel cross-sectional geometry, channel slope, channel hydraulic roughness, and the ice-formation process itself. The existence and layout of large roughness elements, such as large cobbles and boulders, also seem to play a significant role.

Observations during winter 2016–17 suggest that the ice-formation process in the flood-prone reach had difficulty reaching Step 5, “Formation of a complete surface-ice cover,” due to the diversion of water out of the channel. Observations also suggest that if the flow is diverted out of the channel before the MIAWL is reached, the MIAWL may not be reached for a considerable period of time, if at all. The diversion of flow out of the channel seems to slow the rise in water level and prevents, or at least significantly delays, the channel from becoming completely ice covered. Out-of-bank flooding can then continue for a considerable period, as well.

Recall that the flow in Ship Creek is in recession throughout the winter, as shown in Figure 14. In some way, not clearly understood at this time, the flow rate of the channel influences the MIAWL. Certainly it was observed during winter 2016–17 that the entire flood-prone reach was ice covered by the end of February. Mechanical removal had ended at that time, and the flow was entirely contained within the channel. The ice-formation process had reached Step 6, “Anchor-ice detachment and ice-dam breaching,” throughout the flood-prone reach. The flow was then confined to small passages at the channel bed, and flooding was no longer an issue.

6 Winter 2016–17 Field Study

The study team observed the ice conditions in Ship Creek five times during winter 2016–17 (Table 10):

14–16 Nov. 2016. This was before the start of ice formation on Ship Creek. Several cross sections were surveyed. Time lapse cameras were installed in the flood-prone reach. A general inspection of Ship Creek was made from the Ship Creek Dam downstream through JBER.

12–15 Dec. 2017. This was during the ice-formation period. Out-of-bank flooding was observed in the flood-prone reach. Ice thickness was measured at several cross sections. The bulldozers removed ice during this time.

9–13 Jan. 2017. The ice-formation reach of Ship Creek was completely ice covered except for portions of the flood-prone reach. Ice thickness was measured at several cross sections. The bulldozers removed ice during this time. Anchor-ice porosity was measured. (Porosity ranged from 0.14 to 0.28.) A general inspection of Ship Creek was made from the Ship Creek Dam downstream through JBER.

1–2 Mar. 2017. The ice-formation reach of Ship Creek was completely ice covered, including throughout the flood-prone reach. Ice thickness was measured at several cross sections.

17–20 Apr. 2017. Melt out was proceeding throughout the upper portion of the ice-formation reach of Ship Creek. Melt out continued through the flood-prone reach. A general inspection of Ship Creek was made from the Ship Creek Dam downstream through JBER.

Table 11 summarizes the field measurements. Figure 34 provides the cross section locations. Figure 35 shows the results at Section 1, located immediately upstream of Grady Road Bridge, for 14 December 2016.

Table 10. Winter 2016–17 field study.

Date	Crew	Purpose
14–16 Nov. 2016	A. Gelvin, S. Saari	Survey cross sections
12–15 Dec. 2016	A. Gelvin, S. Saari	Ice-thickness measurements and observed mechanical removal
9–13 Jan. 2017	A. Gelvin, S. Daly, M. Reilly-Collette, J. Rocks	Ice-thickness measurements and observed mechanical removal
1–2 Mar. 2017	A. Gelvin, S. Daly	Ice-thickness measurements
17–20 Apr. 2017	A. Gelvin, S. Daly	Ice-thickness measurements and observed melt out

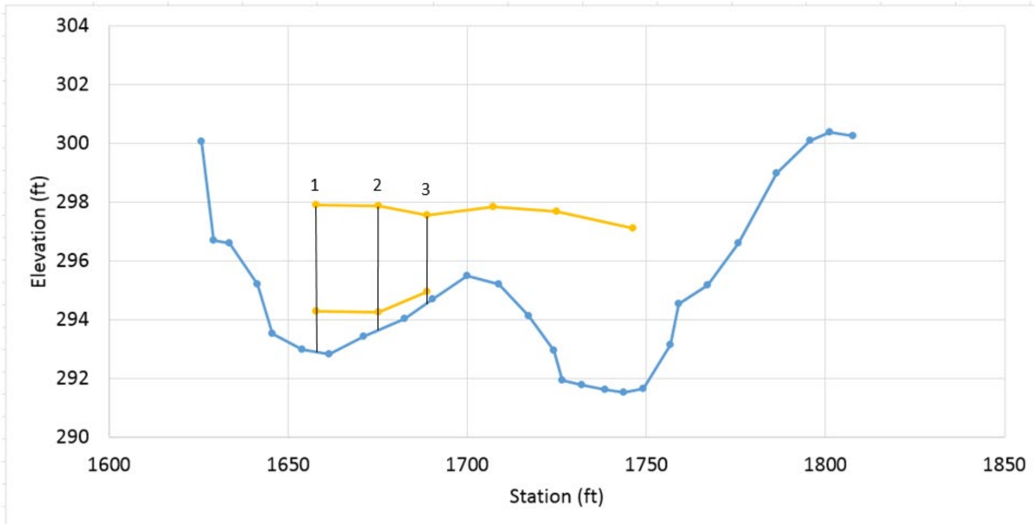
Table 11. Summary of cross-section survey.

Cross Section	Water Elevation[1] (ft)	Average Top of Ice[1] (ft)			Average Ice Thickness (ft)		
		Dec.	Jan.	Mar.	Dec.	Jan.	Mar.
1	1.51	6.14	5.74	-	3.28	2.10	-
2	1.67	4.36	4.30	-	1.41	1.44	-
3	1.08	3.87	5.51	4.13	2.13	1.80	1.64

[1] Above channel thalweg

Figure 34. Ice survey cross-section locations.

Figure 35. Top and bottom of ice on 14 December 2016 at Section 1.



7 Ice-Control Options

Structural control (Tuthill 1995) is probably the most widely used approach for ice control. However, structural control methods, such as floating booms and weirs, are not applicable to Ship Creek due to its steep slope. Nonstructural ice control (Haehnel 1998) is more applicable. There are three approaches that are likely to be successful:

- *Mechanical removal* using bulldozers has been successful over many years. Section 7.1 suggests modifications to optimize the current mechanical removal approach.

- *Bank Modification*, reviewed in section 7.2, would add berms to the overbank areas of Ship Creek to ensure that the maximum water elevations produced by ice formation would be contained within the channel.

- *Thermal suppression* occurs naturally on Ship Creek. Groundwater inflow keeps the lower portion of Ship Creek free of ice each winter. Section 7.3 analyzes the use of groundwater from existing wells located near the flood-prone reach for preventing ice formation in Ship Creek throughout this reach.

7.1 Mechanical removal

Mechanical removal of Ship Creek ice by bulldozers operating in the creek has been an effective method for relieving and preventing ice-affected flooding, as described in section 3. There are two main objectives of mechanical removal. The first is removal of anchor ice and ice dams from the Ship Creek channel bed to increase the flow area of the channel and to lower the water levels. The second objective is to break up and remove the surface-ice cover downstream to provide room for the ice removed upstream to deposit without causing flooding.

Mechanical removal has several disadvantages. Operating bulldozers in the channel of Ship Creek stresses the equipment, leading to breakage and failure; exposes the machines to inundation with subsequent risk of failure of their electrical systems; exposes the operators to extreme cold and wet conditions that require specialized training and personal protective equipment; and places a financial burden on JBER. Breaking and removing the downstream surface-ice cover places the most stress on the equipment.

Mechanical removal can be optimized to minimize disadvantages and still be an effective method for relieving and preventing ice-affected flooding. The following are recommendations for optimizing mechanical removal.

- Closely monitor ice formation in the flood-prone reach of Ship Creek. Anchor ice and ice dams cause the water level of the creek to rise. These ice formations are clearly visible to observers on the banks of the channel. The area to monitor starts at Grady Road Bridge and extends downstream to the section of Ship Creek immediately below the residences in the fish hatchery area. Figure 36 indicates the reach with a solid red line. Most of this area of Ship Creek is visible from the access roads. The formation of anchor ice can begin as early as November. Ice removal was also observed downstream to the steam line bridge, as shown by the dotted red line in Figure 36.

- Begin mechanical removal when the first anchor ice and ice dams appear in the channel of the flood-prone reach.

- Remove the anchor ice and ice dams from the channel on a regular basis. The rise in water level caused by ice should not be allowed to exceed 6 in. to 1 ft. The rate that the ice forms will depend on the air temperature. The anchor ice and ice dams may need to be removed every few days during particularly cold periods.

- Focus the mechanical removal on removing the anchor ice and ice dams from the channel bottom only. Avoid fracturing and removing downstream surface ice if possible. Anchor ice cannot form in reaches with an ice cover in place. Removing the anchor ice on a regular basis reduces the volume of ice that the flow will transport downstream at any one time. The anchor ice tends to be soft and "fluffy" and may be transported a long distance before depositing. This reduces the need to fracture and remove the downstream surface ice and may eliminate the need altogether.

- Tolerate some increase in the water level in the downstream portion of the flood-prone reach as long as it does not lead to local flooding. Increases in water level will tend to promote the formation of a surface-ice cover.

- Continue mechanical removal as long as anchor ice and ice dams are actively forming and flooding is likely. Anchor ice and ice dams will actively form only as long as open water exists.

- Once a section of Ship Creek becomes entirely ice covered, stop mechanical removal in that section as long as the water level is not causing flooding. Once a section of Ship Creek becomes entirely ice covered (no open water is visible), it has reached its MIAWL. The water level in that section should not increase further as the winter progresses, and there is little likelihood of flooding.

Figure 36. Mechanical removal area of the flood-prone reach (*red line*).

7.2 Bank modification

Levees, flood walls, and berms are types of barriers that prevent flooding by containing floodwaters in the channels. In most areas of the U.S., the high-water elevations contained by the flood protection barriers result from large water flows in the channels. The water flow in Ship Creek during flooding is actually low and declines continuously throughout the winter. In Ship Creek, high water results from ice formation in the channel, as described in section 5. Observations suggest that the high water resulting from ice formation is limited by the MIAWL that can occur in the channel.

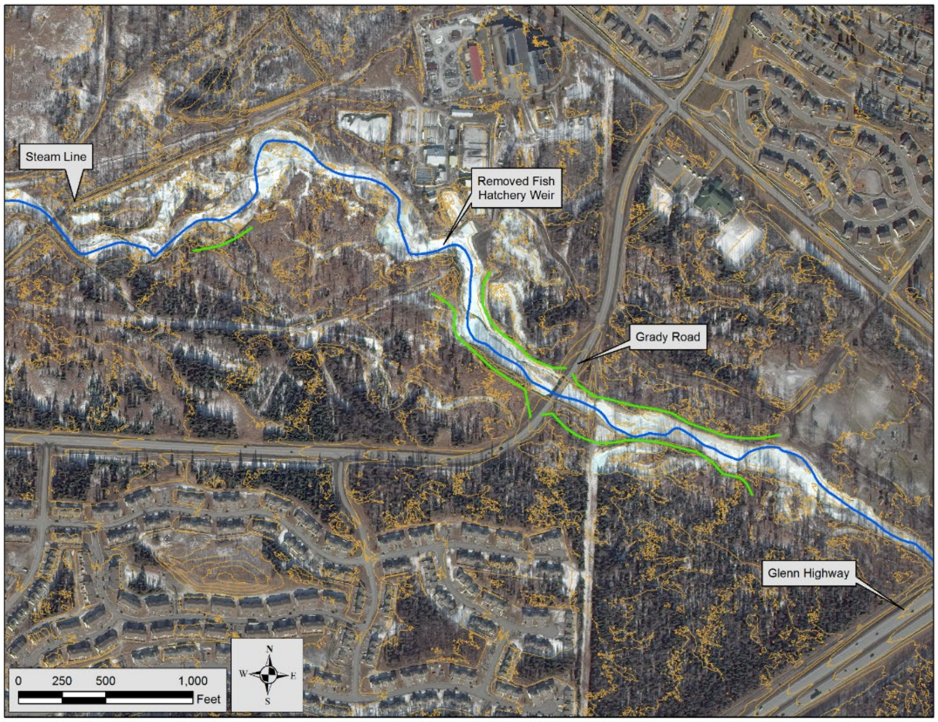
The MIAWL occurs at or near the time that the entire water surface of the Ship Creek channel becomes covered by ice.

Observations during winter 2016–17 showed that the MIAWL was contained within the Ship Creek banks from the Ship Creek Dam downstream to Grady Road Bridge and from upstream of the steam-line crossing downstream to below Vandenberg Avenue Bridge. During winter 2016–17, the water levels exceeded the elevations of the channel banks only in the flood-prone reach, that is, downstream of Grady Road Bridge to below the fish hatchery. When the water levels exceeded the elevation of the channel banks, flow was diverted out of the channel; and out-of-banks flooding occurred.

It should be possible to prevent flooding due to ice formation in Ship Creek by modifying the cross-sectional geometry of the channel to allow the MIAWL to be attained at each point along the creek while containing the flow in the channel. Unfortunately, as stated previously, it is not possible, at this time, to estimate the MIAWL for a given channel section. Understanding the factors that control the MIAWL and developing useful guidelines for estimating the MIAWL should be an important focus of further study. Factors that could likely influence the MIAWL include the flow rate, channel cross-sectional geometry, channel slope, channel hydraulic roughness, and the ice-formation process itself. The existence and layout of large roughness elements, such as large cobbles and boulders, also seem to play a significant role.

The construction of small berms in specific, limited locations is likely to be sufficient to allow the MIAWL to be attained while containing the flow in the channel. Maps of low bank elevations in the flood-prone reach and immediately upstream were prepared to determine the most likely locations for berms (Figure 37). Questions for further study include the placement of the berms with reference to the existing channel banks and the top-of-berm elevations. Understanding the factors that control the MIAWL and developing useful guidelines for estimating the MIAWL should help to answer these questions.

Figure 37. Likely berm locations to contain freeze-up (*green lines*).



7.3 Thermal suppression

Thermal suppression of ice formation occurs naturally on Ship Creek. Groundwater inflow keeps the lower portion of Ship Creek free of ice each winter. This section determines the required groundwater to keep the flood-prone reach of Ship Creek ice-free and compares it to the existing groundwater resources described in section 4.4.1. Appendix B describes the procedure for estimating the required groundwater.

Thermal suppression of ice formation works by keeping the Ship Creek warmer than 32°F (0°C). Ice can only form when the water temperature is at (or below) 32°F (0°C). The actual amount the temperature of Ship Creek is above 32°F does not matter for thermal ice suppression to work. It only matters that the water temperature is above 32°F by some amount. However, this analysis uses a practical limit of the minimum water temperature of 32.18°F (0.1°C). The analysis proceeds as follows:

1. The groundwater is introduced into Ship Creek at the upstream end of the flood-prone reach at Grady Road Bridge.
2. While this study does not include the details of the groundwater outfall into Ship Creek, this analysis assumes that the groundwater is completely

mixed across the creek (horizontally) and from the surface to the bottom of the creek (vertically) when it is introduced into Ship Creek. The groundwater outfall would need to be properly designed to achieve complete horizontal mixing, but it does not seem that this would be difficult. Rapid and complete vertical mixing would be expected in a steep, swiftly flowing channel like Ship Creek.

3. The study assumes the upstream temperature of Ship Creek to be slightly supercooled (31.91°F, −0.05°C).
4. The heat loss between the water and the air is modeled as the temperature difference between the water and air multiplied by a heat-transfer coefficient.
5. The water temperature is modeled as one-dimensional flow using the presentation of Gosink (1986). One-dimensional flow implies that the creek temperature will vary only along the stream and not in the vertical direction or across the stream. This seems very appropriate given the rapid vertical mixing and relatively narrow width of Ship Creek.

The major parameters are the Ship Creek flow rate, the air temperature, and the temperature of the groundwater. It was decided for this study to model October 2007 through May 2015 using the observed Ship Creek flows (USGS 2017), air temperatures (National Weather Service 2017), and groundwater temperatures (A. Tesch, pers. comm.) as shown in Figure 19. The groundwater temperature observations ended in November 2014, but they were extended to May 2015 using the daily average values for each winter day for the missing values.

This study modeled two scenarios. Each scenario assumed a different length for the protected length of Ship Creek. The first scenario was to prevent ice formation in the flood-prone reach from Grady Road Bridge downstream to the steam-line crossing, a distance of approximately 4230 ft (Figure 38). The second scenario was to prevent ice formation in the flood-prone reach from Grady Road Bridge downstream to below the fish hatchery, a distance of approximately 2385 ft (Figure 39).

Each protected reach was divided into sections, approximately 200 ft apart on average. The water depth and water velocity at each section had been estimated for a range of flows by using a previous study (Weston Solutions 2011) and were available in table form. The required values of these parameters were found at each section and each time step by interpolating these tables.

Figure 38. Thermal-suppression Scenario 1, Grady Road Bridge to steam-line crossing.

Figure 39. Thermal-suppression Scenario 2, Grady Road Bridge to downstream of the fish hatchery.

The temperature model was run for each day between October 2007 and May 2015 that had air temperatures below 32°F. (The model was not run for days when the air temperature was greater than 32°F because ice would not form in those days.) On each day, the Ship Creek flow rate, the air temperature, and the groundwater temperature were set based on the observations. The analysis first made an initial estimate of the required groundwater discharge. The groundwater discharge was added to the Ship Creek flow to estimate the total discharge downstream of Grady Road Bridge. The simulation then started with the water temperature at the downstream limit of the protected reach at 32.18°F (0.1°C). Then the Ship Creek water temperature required to provide this temperature was estimated at the next upstream section, based on the total flow and the air temperature. This was repeated section by section, upstream to Grady Road Bridge. The groundwater flow required to provide the estimated temperature at Grady Road Bridge was then calculated. If this estimate matched the initial estimate of the required groundwater discharge, then the simulation ceased for that day and moved to the next day. If the estimate did not match the initial estimate, then a new estimate was made and the simulation rerun. This process was repeated until the initial guess and the final calculated groundwater discharged matched to within a small differential.

Table 12 summarizes the results. Shown are the average and maximum flow rates required for each scenario. This can be compared to the average ADF&G well production of 3735 gpm that was observed for the period 2006–11 (see Figure 18). On average, the ADF&G well production can meet the requirements to suppress ice for both scenarios, although some of the maximum requirements may not be met.

Table 12. Summary of required groundwater flows for thermal suppression.

Parameter	Scenario 1	Scenario 2
Length (ft)	4230	2385
Average Groundwater flow (gpm)	2471	1942
Max Groundwater flow (gpm)	6730	3930

Figure 40 shows the daily groundwater requirements for Scenario 2 for 2007–15. (The groundwater requirements for Scenario 1 look similar except slightly larger and are not shown for convenience.) The average ADF&G well production of 3735 gpm is shown by the red line, demonstrating that the ADF&G average production can meet the requirements except for a few days over the period 2007 through 2015. Figure 41 shows the statistics of groundwater requirements for each day of winter.

While the average ADF&G well production could handle most of the requirements for either scenario, using the ADF&G wells for this purpose would require that most, if not all, the wells be reestablished. The ADF&G wells have not operated since 2014 and were on reduced flow during 2011–14. As mentioned in section 4.4.3, some electrical equipment has been removed, and the current condition of the well field is not known (A. Tesch, pers. comm.). The operation of the well field was not turnkey but required constant attention. As reported by Andrea Tesch (pers. comm.) “The contribution of the shallow wells was extremely variable. As the water level in the aquifer rose and the shallow wells became more productive, we would turn off some wells. If the water level in the aquifer dropped (either from dozers breaking up ice in the winter, or from a dry spell in the summer), we would be turning wells back on.”

Figure 40. Daily groundwater requirements for Scenario 2. The ADF&G average production is shown in *red*.

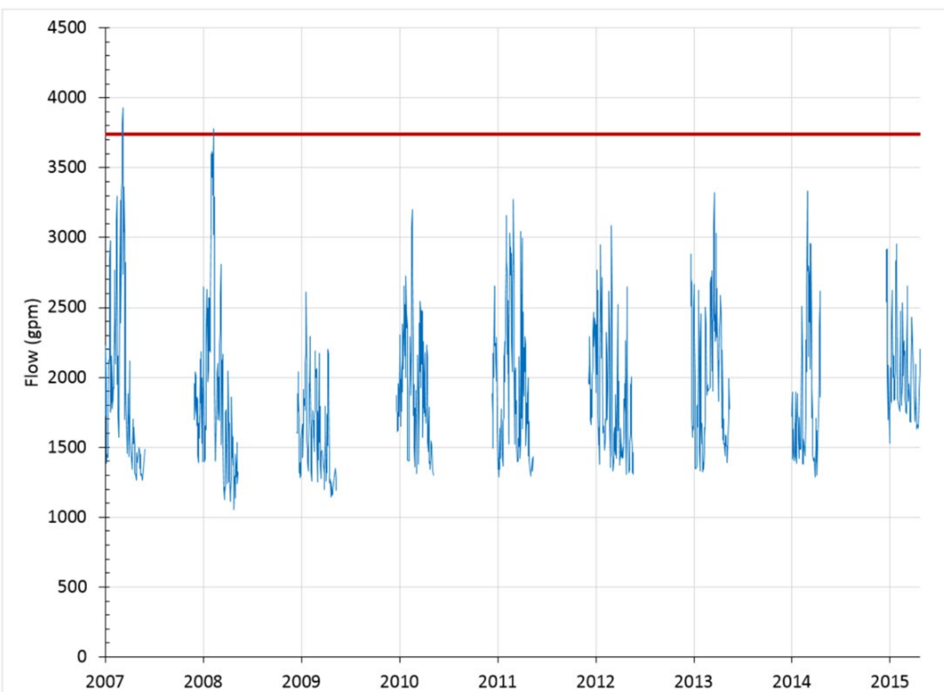
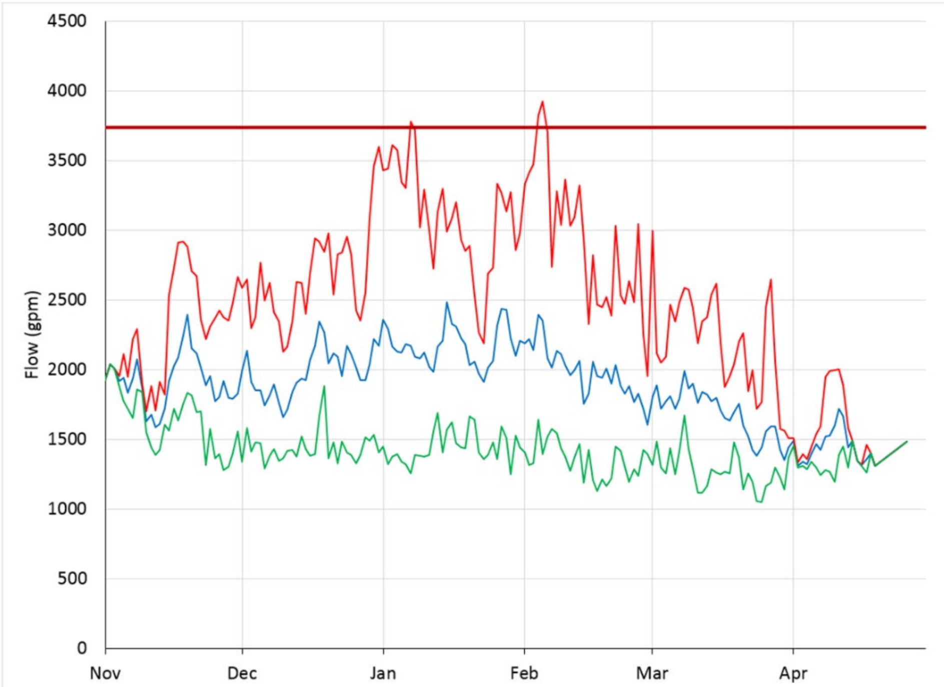


Figure 41. Groundwater requirements on each day of winter: average (*blue*), maximum (*red*), and minimum (*green*).



8 Summary

Ice formation in Ship Creek has caused flooding in JBER and creates the potential for flooding each winter. Mechanical removal using bulldozers operating in Ship Creek to remove the ice and lower the water levels has become an annual requirement to prevent or mitigate flooding.

While anecdotal reports of flooding due to ice formation describe flooding going back many decades, the first reported flooding at the fish hatchery occurred in the winter of 2004. This was soon after the Fort Richardson Power Plant had been decommissioned. Prior to the decommissioning, warm discharge from the power plant and from the Fort Richardson Fish Hatchery apparently suppressed ice production in Ship Creek and prevented the flooding at the hatchery. Significant flooding of the fish hatchery occurred in the winters of 2005–06 and 2016–17. In both cases, mechanical removal relieved the flooding and has been effective in preventing flooding in the other years.

Ice formation in Ship Creek is limited to the reach from roughly Vandenberg Avenue Bridge upstream to the Ship Creek Dam. This reach is steep with relatively high flow velocities. The ice-formation process in this reach is typical of steep channels. The first ice formed each winter is anchor ice and ice dams. Anchor ice and ice dams both cause the water level to rise. After a number of days with frigid air temperatures, the water surface becomes completely ice covered. At this point, the MIAWL in the creek is reached. Immediately afterwards, the anchor ice detaches from the channel bottom, the ice dams breach, and the water level drops. The creek then appears completely ice covered, and the water flow is confined to small passages located under the ice cover at the channel bed. The ice cover does not significantly increase or decrease from this point until spring melt out.

Flooding occurs where the MIAWL caused by anchor ice and ice dams exceeds the elevation of the top of banks of the channel. Areas outside of the channel are then inundated, with the extent determined by the elevation of the overbank areas. Observations during winter 2016–17 showed that the water level rise caused by ice formation was contained within the Ship Creek banks from the Ship Creek Dam downstream to Grady Road Bridge and from upstream of the steam-line crossing downstream to below Vandenberg Avenue Bridge. The water level rise caused by ice exceeded the channel banks downstream of Grady Road Bridge to below the fish hatchery. This is the reach where flooding has occurred.

There are three suitable approaches for ice control to prevent flooding in the flood-affected reach of Ship Creek: mechanical removal, natural bank restoration, and application of well water to prevent ice formation.

Mechanical removal has successfully prevented and mitigated flooding caused by ice since the first onset of flooding in 2004. However, there are a number of costs and disadvantages associated with operating earthmoving equipment in the Ship Creek channel. Section 7.1 provides steps for optimizing the process of mechanical removal.

Out-of-bank flooding could be prevented in the flood-affected reach of Ship Creek if the top-of-bank elevations were increased to contain the maximum water levels that occur during the ice-formation period. It was observed during winter 2016–17 that most of the ice-formation reach of Ship Creek has banks high enough to contain the channel during ice formation without flooding. There is some uncertainty in estimating the required top-of-bank elevations because the type of freeze-up process that occurs in Ship Creek is not quantitatively well described. However, the existing banks in reaches that do contain the maximum stages could be used as guides.

ADF&G developed over twenty wells to supply water to the Fort Richardson Fish Hatchery near the flood-affected reach of Ship Creek. Calculations indicate that well water could be effective in preventing ice formation in the flood-affected reach of Ship Creek if the well production rates and groundwater temperatures that were observed during the fish hatchery operation were realized. The well water would be pumped into Flat Creek of the upstream limit of the flood-affected reach near Grady Road Bridge.

This report is the first to provide a description of ice formation in Ship Creek and resulting ice-affected flooding. Based on this description and the approaches for ice control that are described, it should be possible to effectively prevent ice-affected flooding along Ship Creek in JBER.

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Appendix B: Equations Used in Thermal-Suppression Calculations

The basic equation for river-water temperature in one-dimensional flow is

$$\frac{\partial T_w}{\partial t} + U\frac{\partial T_w}{\partial x} = \frac{\partial}{\partial x}\left(\psi\left(\frac{\partial T_w}{\partial x}\right)\right) + \frac{Bh_{wa}\left(T_a - T_w\right)}{\rho C_p A_f},$$

where

T_w = the water temperature,
U = the flow velocity,
ψ = the longitudinal dispersion coefficient,
x = the distance along the channel,
t = time,
B = the surface top width,
ρ = the water density,
C_p = the water heat capacity,
A_f = the flow area,
T_a = the air temperature, and
h_{wa} = the water-to-air heat-transfer coefficient.

Typical assumptions that the flow temperature does not vary with time at any location and that the longitudinal dispersion effect is small compared to convection lead to the following estimates for water temperature (Gosink 1986) for open-channel flow. This solution to the above equation estimates the water temperature from upstream, Section 1, to downstream Section 2.

$$T_2 = T_1 + \left(T_a - T_1\right)\left(1 - e^{-\frac{h_{wa}z}{\rho C_p U d}}\right),$$

where

T_1 = the water temperature at Section 1,
T_2 = the water temperature at Section 2, and
z = the distance between sections.

The temperature at the upstream limit is found by combining the temperature of the groundwater flow with the temperature of Ship Creek using a simple energy balance:

$$T_1 = \frac{T_{GW}Q_{GW} + T_C Q_C}{Q_{GW} + Q_C},$$

where

T_{GW} = the groundwater temperature,
Q_{GW} = the groundwater flow rate,
T_c = the temperature of Ship Creek water at the upstream limit (assumed to be −0.05°C),
Q_C = the flow rate of Ship Creek, and
T_1 = the fully mixed temperature at the upstream limit.

In practice, the model was run from downstream to upstream. The above solution can be rearranged to solve in the upstream direction:

$$T_1 = T_a + \left(T_2 - T_a\right)e^{\frac{h_{wa}z}{\rho C_p U d}}.$$

After the model has been run from downstream to upstream, the required groundwater discharge is then found as

$$Q_{GW} = \frac{\left(T_R - T_C\right)Q_C}{\left(T_{GW} - T_R\right)},$$

where T_R is the estimated Ship Creek water temperature required at the upstream limit.

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14. ABSTRACT

Ship Creek is a steep, relatively small stream that flows through Joint Base Elmendorf-Richardson (JBER), Anchorage, Alaska. Ship Creek is a losing stream in its upper portion and a gaining stream in its lower portion, and this has significant impacts on the distribution of ice formation in the stream. Ice formation in Ship Creek is limited to the reach from roughly Vandenberg Avenue Bridge upstream to the Ship Creek Dam. This reach is steep with relatively high flow velocities. Anchor ice and ice dams form during freeze-up and raise water levels. Flooding occurs where the maximum ice-affected water level caused by anchor ice and ice dams exceeds the elevation of the top of banks of the channel. Areas outside of the channel are then inundated, with the extent determined by the elevation of the overbank areas.

There are three approaches for ice control to prevent flooding that are suitable for the flood-affected reach of Ship Creek: mechanical removal, application of well water to prevent ice formation, and natural bank restoration. This report explores these approaches and provides recommendations for their effective use.

15. SUBJECT TERMS
Flood control; Ice on rivers, lakes, etc.; Ice prevention and control; Joint Base Elmendorf-Richardson (Alaska)

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